On series-connected renewable generator capable of providing power quality enhancement

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NANYANG
TECHNOLOGICAL
UNIVERSITY

**ON SERIES-CONNECTED RENEWABLE
GENERATOR CAPABLE OF PROVIDING POWER
QUALITY ENHANCEMENT**

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Abstract

Incorporation of renewable generation to low voltage distribution network will have significant impacts on the power quality and the reliability of electricity supply. This is because the renewable power is often based on the harnessing of energy from highly unsteady sources. In this connection, this research work begins with a review of power quality issues in grid systems and the impacts of distributed renewable generator (DRG) on power quality. In this part of the study, it is shown how incorporating the DRG with ancillary functionality can contribute toward reinforcing the distribution grid and improves the power quality of the supply system. As photovoltaic (PV) is one of the most promising renewable energy resources in distribution systems, the study focuses on the design of PV DRG, while taking into consideration the possibility of extending the approaches to other renewable energy resources as well. Furthermore, as series compensation technique is much more effective in maintaining voltage quality of sensitive loads in tightly coupled networks such as the Singapore network, this thesis examines the design of a series-connected photovoltaic generator (SPVG) capable of providing load low-voltage ride-through (LVRT) while maximizing the energy harness from the sun. Analysis of the SPVG operations under disturbance conditions shows explicitly how network voltage quality is affected by the SPVG injected power and its apparent power rating, and that voltage quality can be significantly improved even with a modest level of energy storage capacity incorporated into the SPVG. A control system for the SPVG is also proposed. Both simulation and laboratory tests confirm the efficacy of the proposed distributed generator system.

The study then extends to include a probabilistic analysis of LVRT capability enabled by the SPVG, as a consequence of the stochastic behavior of solar irradiance, load changes and voltage disturbances. A statistical approach is used as a means to assess the effectiveness of the voltage quality enhancement, by treating the input solar power to the SPVG, the load level and the occurrences of voltage disturbances as random variables. The developed statistical model is then utilized to assess the load LVRT capability as it is impacted by the capacity and the aging effect

of the energy-storage capacitor incorporated in the SPVG. The theoretical results are again validated through simulation and laboratory tests.

A generalized approach is then proposed in the thesis to examine the capability of a DRG, incorporated with energy storage system (ESS), in providing load LVRT. With the renewable power, load demand and the occurrences of low-voltage incidents treated as random variables, the probability of successful load LVRT is assessed through the use of copula function to quantify the stochastic dependency between the load and the renewable power. The analysis is subsequently applied to the case of the proposed SPVG incorporated with capacitor energy storage, wherein the focus is to establish the analytical relationship between the probability of successful load LVRT and the rated power/energy capacities of the DRG-ESS. Determination of the optimal capacities of the DRG-ESS is achieved through the maximization of the expected economic benefits obtained from the renewable energy harness and load LVRT minus the cost of the DRG-ESS.

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List of Acronyms

ADC	Analog to Digital Card
ANF	Adaptive Notch Filter
CDF	Cumulative Distribution Function
CEC	Characteristic Equation of Closed-loop
CEO	Characteristic Equation of Open-loop
DAC	Digital to Analog Card
DG	Distributed Generator
DRG	Distributed Renewable Generator
DFT	Discrete Fourier Transform
DSP	Digital Signal Processor
DSTATCOM	Distributed Static Compensator
DVR	Dynamic Voltage Restorer
ESS	Energy Storage System
EPLL	Enhanced PLL
EPRI	Electrical Power Research Institute
ESR	Equivalent Series Resistance
FACTS	Flexible AC Transmission System
FB	Full Bridge
FB-Bipolar	Full Bridge Inverter with Bipolar Modulation
FB-DCBP	Full Bridge Inverter with DC Bypass
FLL	Frequency-Locked Loop
HERIC	Highly Efficient and Reliable Inverter Concept
HVRT	High Voltage Ride-Through
IGBT	Insulated Gate Bipolar Transistor
KS	Kolmogorov-Smirnov
LF	Loop Filter
LVRT	Low Voltage Ride Through
MPP	Maximum Power Point

MPPT	Maximum Power Point Tracking
OSG	Orthogonal Signal Generator
PCC	Point of Common Coupling
PD	Phase Detector
PDF	Probability Density Function
PI	Proportional Integral
PLC	Programmable Logic Controllers
PLL	Phase Locked Loop
PV	Photovoltaic
PVG	PV generator
PWM	Pulse Width Modulation
P&O	Perturb-and-Observe
RDFT	Recursive Discrete Fourier Transform
RHS	Right Hand Side
RTI	Real-Time Interface
RV	Random Variables
SCR	Short circuit ratio
SDRAM	Synchronous dynamic random access memory
SMES	Super Conducting Magnetic Energy Storage
SOGI-PLL	Second-Order Generalized Integrator based PLL
SPVG	Series Connected Photovoltaic Generator
STATCOM	Static Compensator
STS	Static Transfer Switch
SRF-PLL	Synchronous Reference Frame PLL
SSCL	Solid State Current Limiter
SVB	Static Voltage Booster
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
UPS	Uninterruptable Power Supply
VCO	Voltage Control Oscillator
VSC	Voltage Sourced Converter

List of Symbols

Chapter 2:

C_{DC}	DC-link power decoupling electrolytic capacitor
$\bar{E}_S$	phasor of open-circuit voltage of the equivalent grid source
E_S	magnitude of open-circuit voltage of the equivalent grid source
$\bar{I}_i$	injected current phasor
$\bar{I}_L$	load current phasor
I_L	load current magnitude
i_{pv}^*	analytic solution of MPP current
I_S	reverse saturation current
I_{SC}	short circuit current
k	Boltzmann's constant
n	transformer turn ratio
n_s	number of series cell in the PV module
N_s	total number of sag events
P_{MPP}	output power of the PV module at MPP
P_L	load active power
$prob(.)$	probability mass function
P_{st}	flicker severity
q	electric charge
Q_L	load reactive power
R_L	load resistance
R_S	equivalent source resistance
r_s	series resistance of PV module
S_i	complex injected power to the grid
T	operating temperature of PV
V_{DC}	DC-link voltage
$\bar{V}_L$	load voltage phasor

V_L	load voltage magnitude
V_n	nominal voltage of the grid
v_{pv}^*	analytic solution of MPP voltage
$\bar{V}_S$	source voltage phasor
V_S	source voltage magnitude
$\bar{V}_i$	injected voltage phasor
V_i	injected voltage magnitude
V_{OC}	open circuit voltage
X_s	equivalent source reactance
Z_S	equivalent source impedance
ΔV	voltage deviation
α	angle of series injected voltage
β	angle of equivalent source impedance
φ	load power factor angle
δ	angle of open-circuit voltage of the equivalent grid source
λ	angle of shunt injected current

Chapter 3:

a_{io}	coefficient of open-loop characteristic equation where i is degree of the indeterminate (i.e. s^i)
a_{ic}	coefficient of closed-loop characteristic equation where i is degree of the indeterminate (i.e. s^i)
C_{DC}	DC-link capacitor
C_f	filter capacitor
C_{PV}	PV capacitor
$\bar{E}_S$	phasor of open-circuit voltage of the equivalent grid source
E_S	magnitude of open-circuit voltage of the equivalent grid source
$E_{S,l}$	magnitude of grid voltage during sag event l
$E_{SW,j}$	magnitude of grid voltage during swell event j
G_{vlc}	closed-loop transfer function from the v_{L-ref} to v_L

G_{vsc}	closed-loop transfer function from v_s to v_L
G_{vlo}	open-loop transfer function from the v_{L-ref} to v_L
G_{vso}	open-loop transfer function from v_s to v_L
G_k	gain of the k^{th} forward path in Mason's method
K_{inv}	inverter gain
K_v	voltage gain
i_{inv}	inverter current
$\bar{I}_i$	injected current phasor
$\bar{I}_L$	load current phasor
L_f	filter inductance
L_L	load inductance
L_t	transformer inductance
n	transformer turn ratio
P_i	injected active power
P_i^*	output of the DC-link voltage controller
$P_{i,min,l}$	minimum injected active power for event l
P_{i-ref}	reference of active injected power
P_{loss}	inverter circuit losses
P_L	load active power
P_{PV}	Photovoltaic power
Q_i	injected reactive power
Q_L	load reactive power
R_f	filter damping resistance
R_L	load resistance
R_s	source resistance
R_t	transformer resistance
$\bar{S}_L$	complex power of load
S_r	apparent power rating of SPVG
V_{DC}	DC-link voltage
$V_{DC,min}$	minimum DC-link voltage to prevent over-modulation
$V_{DC,n}$	nominal DC-link voltage

V_{DC-ref}	DC-link voltage reference
v_f	output voltage of filter
$\bar{V}_L$	load voltage phasor
V_L	load voltage magnitude
v_L	load voltage
$V_{L,n}$	nominal load voltage magnitude
v_{L-ref}	reference load voltage
$\bar{V}_S$	PCC voltage phasor
V_S	PCC voltage magnitude
v_S	PCC voltage/source voltage
$\bar{V}_i$	SPVG injected voltage phasor
V_i	SPVG injected voltage magnitude
X_S	equivalent source reactance
Z_S	equivalent source impedance
$\Delta T_{max,l}$	maximum duration of the event l when the grid voltage drops to $E_{S,l}$
θ	load voltage phase angle
φ	load power factor angle
ζ_{nc}	damping constant of closed-loop
ζ_{n0}	damping constant of open-loop
ω_{n0}	natural frequency of open-loop
ω_{nc}	natural frequency of closed-loop
ρ	argument of the source voltage $v_s(t)$

Chapter 4:

C_{DC}	DC-link capacitor
I_P	primary current
I_S	secondary current
I_i	injected current
P_i	injected active power

P_{loss}	inverter circuit losses
P_{PV}	photovoltaic power
Q_i	reactive injected power
R_{Gon}	gate on resistor
R_{Goff}	gate off resistor
R_1	external resistor
R_M	measurement resistor
V_{CE}	collector to emitter voltage
V_{DC}	DC-link voltage
$V_{G(on)}$	turn on gate voltage
$V_{G(off)}$	turn off gate voltage
V_L	load voltage magnitude
v_L	load voltage
V_S	PCC voltage magnitude
v_S	PCC voltage
V_i	SPVG injected voltage magnitude
ω_c	center frequency
θ	detected angle

Chapter 5:

A	set of events X and Y
$\bar{A}_{ij}$	time series coefficient of i_{DC} for i and j indices
$\bar{B}_{ij}$	time series coefficient of i_{DC} for i and j indices
C_2	dielectric capacitance
C_{DC}	capacity of electrolytic capacitor
C_{PV}	PV capacitor
$\bar{E}_S$	phasor of open-circuit voltage of the equivalent grid source
$ESR(T, f)$	function of equivalent series resistance
f	frequency

f_s	modulation frequency
G	experimental coefficient in heat transfer equation
H	heat transfer per unit surface area
i_C	capacitor current
$I_{C,0}$	DC component of capacitor current
$I_{C,n}$	n^{th} harmonic content of capacitor current
i_{DC}	DC input current to inverter
$i_{DC,x}$	DC input current to inverter of leg x
$I_{DC,in}$	DC input current to DC- link from DC-DC converter
$\bar{I}_{inv}$	phasor of inverter current (fundamental component)
$\bar{I}_{inv,min}$	inverter output current for the given $P_{i,min}$
I_o	inverter peak current
$j_n(\cdot)$	n^{th} order Bessel function of the first kind
M	Modulation index
N_A	cardinal number of set A
N_h	N_h is the maximum harmonic
N_{PL}	total number of possible discretized P_L
N_{PV}	total number of discretized P_{PV}
N_s	total number of events
N_{Vs}	total number of discretized V_s
P_i	injected active power
$P_{i,min,l}$	minimum required injected active power for event l
P_{loss}	total losses in the DC/AC conversion circuit
$P_{loss,C}$	capacitor loss
$P_{loss,inv}$	inverter loss
P_L	load active power
P_{PV}	PV Output Power
$prob(\cdot)$	probability mass function
Q_i	reactive injected power
Q_L	load reactive power
$\mathfrak{R}_l$	load low voltage ride-through event l

RT	total successful ride-through event
r	capacitor radius
r_e	capacitor element radius
R_0	resistance of the capacitor terminals, foils and tabs
R_1	electrolyte resistance
R_2	dielectric resistance
S	surface area
$S_x(t)$	PWM switching function
T	capacitor temperature
T_0	initial capacitor temperature
T_{amb}	ambient temperature
t_{max}	maximum duration for which load LVRT can be achieved by SPVG
t_s	duration of the voltage sag
$V_{DC,min}$	minimum DC-link voltage
V_{DCn}	nominal DC-link voltage
$\bar{V}_{inv}$	inverter output voltage
$\bar{V}_{inv,min}$	inverter output voltage for the given $P_{i,min}$
$\bar{V}_L$	load voltage
$\bar{V}_S$	source voltage
X_{Lf}	reactance of L_f
X_{Cf}	reactance of C_f
z	capacitor height
Z_L	load impedance
ΔT	element temperature rise
δ	inverter power factor angle
θ	load voltage phase angle
φ	load power factor angle
ψ	SPVG power factor angle
σ_x	width of the interval used in the discretization procedure
σ_v	inverter voltage phase angle
σ_i	inverter current phase angle

δ	inverter power factor angle
δ_{Vs}	voltage sag bin width used in the discretization procedure of V_s
δ_x	bin width used in the discretization procedure of X
δ_y	bin width used in the discretization procedure of Y
ω_c	carrier angular frequency
θ_{cy}	carrier phase angle
θ_{ox}	fundamental phase angle of phase x
ρ	experimentally measured coefficient for ESR calculation formula
γ	experimentally measured coefficient for ESR calculation formula
ζ	experimentally measured coefficient for ESR calculation formula

Chapter 6:

B_G	total economic benefit of energy harnessed and exported by the DRG-ESS in a year
B_R	economic benefit when a successful load LVRT is achieved
C_{DC}	capacity of capacitor ESS
C_{ESS}	annualized cost of the ESS
C_{RG}	annualized cost of the DRG
F_{Pg}	marginal distribution function (i.e. CDF) of the random variable P_g
F_{PL}	marginal distribution function (i.e. CDF) of the random variable P_L
F_{PgPL}	joint cumulative distribution function of the random variables P_g and P_L
$\bar{E}_S$	phasor of open-circuit voltage of the equivalent grid source
N_g	total number of discretized P_g
N_k	number of sag events with magnitude $V_{s,k}$ per year
N_{Vs}	total number of discretized V_s
N_{PL}	total number of possible discretized P_L
P_g	DRG generated power
P_g^*	P_g transferred in the rank domain

P_i	injected active power
$P_{i,min,l}$	minimum injected active power for event l
P_{loss}	total losses in the DC/AC conversion circuit
P_L	load active power
P_L^*	P_L transferred in the rank domain
$prob(.)$	probability mass function
Q_i	reactive injected power
$\Re_l$	load low voltage ride-through event l
RT	total successful of ride-through event
t_{max}	maximum duration for which load LVRT can be achieved by SPVG
t_s	duration of the voltage sag
$V_{DC,min}$	minimum DC-link voltage
$\bar{V}_L$	load voltage phasor
$\bar{V}_S$	source voltage phasor
w_k	weighting factor to reflect the benefits of sag event k
X	random variable
X_j	discrete value of X over the interval j
Z_S	source impedance
θ	load voltage phase angle
φ	load power factor angle
σ_g	width of the discretization intervals for P_g
σ_L	width of the discretization intervals for P_L
ρ	linear correlation
ρ_r	rank correlation
λ	performance index of the annualized net benefit of DRG-ESS

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Chapter 1. Introduction

1.1. General Observations

As of present day, the main electrical powers are generated from

- Thermal power plants, the main sources of the energy are fossil fuels such as coal, oil, and natural gas;
- Hydroelectric power plants which derive their energy from the stored potential and kinetic energy of water in rivers and lakes;
- Nuclear power plants where uranium is the main fuel;
- Environmentally-friendly or green-power generation from renewable energy sources. A renewable energy source is an energy resource from nature and comes free without emission such as sun, wind, geothermal, ocean energy (i.e. wave and tidal) etc.

After the sudden and drastic increases in oil price in the 1970s and other political issues in the Middle East, finding alternative and secure energy sources (including that for electricity generation) has attracted much attention world-wide. On another front, combustion of the fossil fuels pollutes the environment and produces harmful gases such as NO_x, SO_x, CO and CO₂. NO_x and SO₂ in the presence of water in the atmosphere form acids causing acid rains. Acid rain has negative impacts on human health, plants life and soil. With regard to CO₂, thermal power plants are major sources of CO₂ production because the electricity production is from the burning of the fossil fuels [1]. CO₂ is a greenhouse gas and the increase of CO₂ in the atmosphere disrupts the balance between the production of CO₂ and its conversion back to plants. It results in temperature on earth to increase. It has been established that global temperature has raised by about 2°C compared to pre-industrial time.

Temperature change affects the environment and climate dramatically. Thus it can be concluded that to rely on the traditional carbon-based fuels such as coal, oil and gas to meet the steadily increasing global energy demand is unsustainable as the fuels are exhaustible resources and the combustion of these fuels pollute the environment.

One possible and attractive solution is to adopt nuclear power. However, this type of power generation comes with the attendance issues on safety, i.e., contamination and spreading of the radioactive materials over vast area due to accidents/mishaps. After the recent Fukushima nuclear disaster, a number of planned nuclear power programs are being re-evaluated in many countries and it is expected that many of the existing nuclear plants may be closed as a result of the Japanese nuclear incident.

In view of the above factors, developing viable renewable sources for electricity production has attracted much attention in recent years [2, 3]. Renewable resources are potential sources for increased security of energy supply and they can contain the risk of mal-operation or accidents within acceptable level, in contrast to (say) that of using nuclear energy. Indeed in an impactful meeting in Kyoto in 1997, a global treaty was agreed by many economies concerning the production of renewable energies and achieving other so-called “green” objectives. The main initiatives are to include the reduction of fossil-fuel power generation and thus decrease greenhouse gas emission, and to use more efficient devices to decrease the growth in energy demand, among other recommendations.

Regarding carbon-free renewables, they include:

- **Solar energy:** Photovoltaic systems can directly convert energy of light photons to DC electricity using the P-N junction of PV cells. The output power of the PV systems depends on solar irradiance, temperature and surface area. The PV power is however strongly weather dependent. Another technology is called solar-thermal power generation. It is based on the conversion of sun energy to electricity using curved mirrors to concentrate solar irradiance onto a fluid container, called receiver, to produce heat. The thermal energy is then transformed to electricity using Stirling or steam engines.

It is expected PV power generation would become the second largest renewable source by 2040 because of the huge cost reduction of PV systems and its flexibility in power generation [2]. It is estimated that the market of solar thermal electricity would be similar to that of wind power but with a twenty years delay. Expected annual growth rates for PV and solar-thermal power are about 30% and 22 % respectively [2].

- **Wind energy:** In this renewable energy technology, a wind turbine converts the kinetic energy contains in the wind to electricity. Typically the main mechanical means in the conversion is through the use of a two- or three-blades horizontal axis turbine. The turbine is often coupled to an induction generator: specifically a doubly-fed induction generator or a generator with power electronic interface. In recent years, many countries have undertaken expansions to install large wind parks. While small wind parks in the range of 3-10 turbines are usually connected to medium voltage distribution systems, large wind parks could be connected to sub-transmission or transmission networks [4]. The annual growth rate of wind power generation has been more than 30% for the last few years, although currently, the rate has reduced to some 20% [2]. It is expected that the growth rate of wind power generation shall decrease continuously from now on and after 2040, it will tend to zero.

- **Tidal Power:** The periodic rise and fall of the water level along coasts due to the rotation of the moon around the earth causes the tidal stream. This stream can be used to rotate tidal turbines and generate power. Another scheme is to use tidal barrage to trap water at high tide and exploit the energy from the discharging water. The physical operating principle of the tidal in-stream turbines is mostly similar to the wind power conversion systems, i.e. the extracted stream power is proportional to the density of seawater and cube of its speed [5].

The number of suitable locations for tidal power generation is limited to some geographical locations: For example India, Australia, United Kingdom and United States. Theoretical estimated potential of tidal could be more than 150 TWh per annum [6]. In term of existing installations, a 240 MW tidal power plant has been installed in France in 1966 [7, 8]. Another large tidal current power station, with capacity of 254 MW, is in operation in South Korea since 2011 [8].

▪ **Wave power:** Wave power is less predictable compared to tidal power but it is more readily available compared to tidal. Hence, wave turbines can be installed in many coastal locations and they can be connected to distribution grid. Several pilot plants have been installed but some technical challenges have limited the global development of this kind of distributed renewable generators (DRG). For example, the wave energy can vary from 5 kW/m in summertime and up to 1000 kW/m in winter [9]. Designing a turbine which can handle such wide range is very challenging [4].

Wave and tidal energies are anticipated to be important electrical energy contributors after 2020. The annual growth rate before 2020 is predicted to be 15% and increases to more than 20% subsequently.

▪ **Hydro power:** The flow of water is used to generate electricity in this mode of production. The most common way of the hydro power electricity generation is to utilize reservoir behind a dam and converts the potential energy of water to kinetic energy and thence to electricity using turbines. Using natural water flow to rotate a small generator is an alternative way to produce power in small scales. The capacity range of hydro power electricity generation could be from hundreds of kilowatts to several thousands of megawatts. Unfortunately, the exploitation of large hydro power is limited to some geographical regions. It has been reported that there is limited scope of significant potential sites for development of large hydro in the world, although the potential of small hydro is more promising. The expected growth of small hydro exploitation until 2020 could be 10%, while for the large hydro, the growth is about 1 % [2].

Among the above renewable energy technologies, harnessing the energy from the sun using photovoltaic (PV) modules integrated into low-voltage distribution networks has seen significant growth [10]. This form of energy harness has excellent potential as a photovoltaic (PV) module does not contain any moving parts, and could have long service life and requires low maintenance. Furthermore, the energy captured by the PV module is environmental friendly and inexhaustible. Indeed, PV power generation is one of the most promising methods among the various renewable technologies. One witnesses a steady increase in the amount of PV power generation

Fig. 1.1 Development of Annual PV Installations.

in grid systems [2, 3, 10, 11]. Fig. 1.1 depicts the annual growth of PV installations within the last two decades. Most of PV installations are grid-connected generators. Off-grid power generation market is small compared to the grid-connected systems, although off-grid PV enjoys rapid growth rate in some countries such as India and Bangladesh where there are shortage of electricity in the areas not served by traditional grid infrastructure [11].

1.2. Motivation

In view of the above observation, it is not surprising to note that there is intense interest in recent years on the integration of distributed renewable generation (DRG) into grid systems. Unlike conventional generators, however, output power of a DRG is often unsteady because the input power from its renewable sources tends to fluctuate. Thus, in addition to supplying electricity to the load, it would be most desirable if any negative impacts induced by the fluctuating renewable power could be mitigated through appropriate means so as to enhance the reliability and security of the electricity supply systems [12-14].

In this connection, active research works have been reported in the literature pertaining to the provision of voltage quality enhancement capability using suitably-

designed DRG [13-17]. Indeed, these generators are stipulated to provide reactive power support in order to comply with the prevailing grid codes [18-20].

As pointed out in Section 1.1, PV power generation is one of the most promising renewable sources. The expected cost reduction and the flexibility of the PV systems is predicted to make PV the second largest contributors among all renewable energy candidates by 2040 [2]. Among the PV distributed generators, small PV generators connected to low voltage distribution networks have seen significant growth [13, 21]. Indeed the installation of single-phase grid-connected PV generators is growing steadily due to load increases, cost reduction of PV generators and the maturing of the PV technology [3, 22].

Notwithstanding these advantages, increasing the level of penetration of the PV systems into grids often results in negative impacts on supply reliability and security. Hence, much research work has been reported on integrating PV systems which not only harness solar energy but also perform other functionalities such as power quality enhancement [13, 23-25]. Technical challenges considered in the design of the PV DRG systems include for instance, the rapid changes in solar irradiance may introduce sudden variations of voltage. Conversely under low load condition and when there is high level of PV power generation, customer may experience overvoltage.

In terms of meeting the challenge on supply security, three common PV power smoothing techniques are based on energy storage systems (ESSs), dump loads, and the restriction of the generated solar power below the maximum power point [26]. So, in order to curtail power fluctuations which may only last for a few seconds, conventional battery ESS would not be a suitable solution. Other types of ESS such as capacitors or combination of battery and capacitor would be more suitable for the power buffering task [27] although further work is required to reduce the ESS cost. Elimination of the voltage fluctuations induced by the DRG using variable reactive power is an alternative solution [5, 28-34], although this method is effective in mostly inductive transmission grid systems. In a transmission system such as the Singapore underground cable network in which the network resistive component

cannot be ignored, the control of active power flow in the network should be incorporated in conjunction with reactive power regulation.

While the above is pertaining to the normal steady-state operations of network systems, power quality surveys have shown that voltage sags are the most severe power quality disturbances. While a voltage sag is not as severe as compared to an interruption, voltage sags are more frequent events than interruptions and affect widely-used sensitive electronic equipment. It is expected that the ride-through capability of single phase grid-tie PV generators during grid fault will become more vital in providing grid voltage support in the near future. Voltage quality must be kept to acceptable degree during normal or fault condition [21, 35-38]. In this connection, several mitigation techniques have been proposed to provide such “ride-through” capability against voltage sags. Series compensation is the most effective method to provide such ride-through in strong or “stiff” power systems. As shall be shown in Chapter 3 of this thesis, series compensation needs an additional energy storage device to mitigate severe voltage sags due to the requirement of active power injection. Therefore, the potential of combining the series compensation and renewable power generation is a fruitful area of investigation. Due to the intermittent behavior of renewable resources, in order to ride through voltage disturbances, it shall be shown that an ESS is necessary to provide the necessary injected active power. One way is to incorporate capacitor into the power- electronic based DRG. So instead of using a separate energy storage, with appropriate design, the DC-link capacitor can provide the required active power to mitigate voltage sags. The DC-link capacitor can only store limited amount of energy. However, as the duration of a voltage sag is usually less than 1 sec, therefore with appropriate design of ESS, the DRG can significantly enhance power quality without the need of additional energy storage medium. However, economical design of a DRG capable of providing power quality enhancement requires a statistical instead of deterministic approach. This is because load, renewable power and voltage disturbances are time-varying random variables. Hence deterministic approach could lead to less cost-effective design. A probabilistic approach has been proposed in this thesis. Specifically, in order to improve the power quality of loads, a series-connected PV generator has been

examined for low-voltage distribution systems. It can mitigate voltage disturbances, suppress harmonic and provide reactive power support as well.

1.3. Objectives

The focus of the research described in this thesis is to propose and develop appropriate techniques to improve the voltage quality in the grid systems which contain significant amount of renewable power generation.

The main objectives of this research project are as follows:

- To investigate the impact of DRGs on power quality of distribution networks.
- To review the existing renewable power generator control strategies, with the view to improve the likelihood of load low-voltage ride-through.
- To develop a new photovoltaic generator capable of generating power as well as voltage quality enhancement.
- To determine the capacity of the energy storage system required to assist the PV generator to achieve successful voltage sag mitigation.
- To develop a new statistical method to assess the low voltage ride-through capability of renewable generators and the design of a suitable power quality conditioner.
- To verify the effectiveness of proposed methods through numerical calculations, simulation and experimental measurements.

1.4. Major Contributions

The main contributions and highlights of the thesis are summarized as follows:

- A proposed series connected PV generator (SPVG) has been analyzed in detail and using the developed method to control the active and reactive power flows of the SPVG, the load voltage can be maintained constant during voltage sags/swells;

- A capability diagram has been derived which can be used to quantify the constraints on the active and reactive power flows during the voltage compensation stage so as to prevent the PV generator from overloading.
- A mathematical model for the proposed SPVG has been developed. The proposed controller is relatively simple to design and the computational burden required to effect the voltage quality enhancement is less than that required by existing controllers used in single-phase PV inverters.
- The performance of the proposed system has been studied and evaluated by means of simulations. The results are further validated experimentally in the author's laboratory.
- Due to the intermittent behavior of solar irradiance and the stochastic nature of voltage disturbance and load demand, a statistical method to evaluate load low-voltage ride-through capability of SPVG has been proposed.
- A method to determine the required capacity of the capacitor ESS to achieve given voltage enhancement capability. The impact of capacitor energy storage in voltage quality enhancement of SPVG is studied and a statistical method proposed to determine the most effective capacitor ESS capacity has been developed.
- A general statistical method is proposed to quantify the impacts of distributed renewable generator in voltage sag mitigation. Due to possible statistical correlation between load and renewable power, a new technique to design the DRG-ESS has been proposed.

1.5. Thesis Organization

In addition to the introductory chapter, this thesis comprises the following chapters:

Chapter 2 presents a literature review on power quality issues, mitigation techniques, integration of renewable generators (particularly of PV) to grids, and the impacts of renewable generators on power quality. A brief explanation to show why

a probabilistic method is suitable to evaluate the impacts of PV system on power quality is presented. As voltage sags and swells are the most severe disturbances that can degrade power quality, therefore in this chapter, voltage sag/swell issues are specifically considered in terms of the sources of the sags/swells. Existing mitigation devices shall be described. The devices can be broadly categorized as based on shunt compensation, series compensation and combination of shunt and series compensation. On the generation side, the impacts of distributed generation on voltage quality are also included in the chapter. Methods which can reduce the power quality degradation associated with DRGs are shown. Major grid regulations required to integrate DRGs into the grid are listed.

A new series-connected photovoltaic generator (SPVG) is proposed in Chapter 3. The design of the SPVG is such that it not only maximizes energy harness from the sun, but it also attempts to maintain high voltage quality when upstream voltage disturbances occur or when the input solar power fluctuates. The SPVG is a renewable distributed generator with power quality improvement functionality while during periods of low solar irradiance or at night, the SPVG operates as a power quality enhancer. A detailed analysis on the capability of the SPVG in voltage quality enhancement is presented. The necessity of using capacitor ESS in the SPVG is firmly established. A method to determine the required capacity of the capacitor to achieve given voltage enhancement capability is shown. The operating principle, modeling and analysis of the proposed SPVG are presented in this chapter. The design of the control scheme for the SPVG is explained and supported by simulation results.

Chapter 4 explains the hardware implementation of the proposed SPVG and control system. In order to realize an effective control system to mitigate voltage disturbances, grid synchronization and detection of supply voltage parameters (such as magnitude and phase angle) are also described. The voltage quality enhancement capability is verified and compared with the simulation results obtained in Chapter 3. The efficacy of using ESS is demonstrated.

A new probabilistic approach for ride-through capability evaluation of SPVG is presented in **Chapter 5**. Firstly the ageing effect of electrolytic capacitor is evaluated

against the load low voltage ride-through ability afforded by the SPVG. Laboratory test results to validate the analysis and the proposed method are presented. Numerical examples are given to illustrate the proposed design technique.

Chapter 6 presents a generalized probabilistic approach to evaluate the load low voltage ride-through capability of DRG. In this study, the correlation between load and renewable power is taken into account. The method is then applied to a series-connected DRG. The copula concept for the determination of stochastic dependency between these two random variables is described. Numerical examples are used to illustrate the proposed statistical approach.

Chapter 7 presents the conclusions and contributions based on the work presented in the preceding chapters of the thesis. It also contains recommendations for possible future works.

Chapter 2. Power Quality and its Inter-relationship with Distributed Renewable Power Generation

Global concerns for the environment and the sustainability of energy resource are the main drivers for the search of renewable energy sources as alternatives to fossil fuels. Converting energy from wind and the sun into electricity is currently attracting intense interest in many parts of the world because such methods have less adverse impact on the environment. Notwithstanding these advantage, generating electricity from the intermittent renewable sources brings with it some technical challenges, one of which is on power quality. In the following sections, impact of DRG on power quality and some power quality enhancement methods shall be discussed. Thus, Section 2.1 outlines common power quality issues encountered in grid systems. Section 2.2 describes in general mitigation techniques intended for alleviating power quality problems. Section 2.3 explains the impacts of DRG on power quality while some well-established techniques to reduce the negative impacts of the DRGs on power quality are also described. Section 2.4 presents the application of DRGs which not only undertake renewable energy harness, but also plays the role of improving power quality. As the focus of this study is on PV systems, grid codes governing the integration of PV sources into power systems are presented in Section 2.5. A brief explanation to show why a probabilistic method is suitable to evaluate the impacts of PV systems on power quality is given in Section 2.6.

2.1. Power Quality

Power quality pertains to any power problem which manifests in voltage, current, or frequency deviations that results in failure or mis-operation of electrical equipment [39]. Interest into power quality has significantly increased in recent years and the subject has become a most important consideration in the design and operation of electrical power systems. Power quality issues include a wide range of disturbances which can affect electronic equipment in present-day networks. Indeed, low power quality supply could cause large financial losses. Thus providing an acceptable power quality supply is one main expectation of customers in modern grid systems.

Before the improvement of supply quality in a power system is attempted, the types of power quality problems should first be identified. A common way to do so is to record the disturbance events. Each record of the disturbances could contain its magnitude and duration plus possibly a few other attributes. Two types of power quality monitoring need to be distinguished. The first is to monitor the supply at (large) number of locations at the same time to obtain the “average power quality” and is called power quality survey. The second type is to monitor the supply at one site in order to estimate the power quality at the specific site over the long-term.

Several large-scale power surveys have been reported in the open literature [40-48]. Since these surveys have different threshold limits for the voltage disturbances and there are specific purposes for performing the surveys, one may categorize the disturbances based on the results of the four-years power quality monitoring described in [41]:

- **Transient Disturbances**

These take the appearance of oscillatory transients which can last typically at less than 10 ms. A typically cause of the disturbance is capacitor switchings or faults.

- **Momentary Disturbances**

Voltage increases or decreases which may last between 10 ms and three seconds. Momentary disturbances are normally created due to load change or propagation of fault in the power system. The decrease and increase of voltage are usually defined as sag and swell respectively.

- **Steady-state Disturbances**

The steady-state disturbances are usually defined as any increase or decrease of voltage which last more than 3 sec. These disturbances are caused by regulator actions, such as incorrect transformer tap settings or localized faults.

From the surveys, it can be found out that most of the significant voltage disturbances are between 70% - 110% of their rated values. These disturbances are

Chapter 2: Power Quality and its Inter-relationship with Distributed Renewable Power Generation

also categorized as momentary disturbances because most of voltage increases or decreases (swells, sags or interruptions) only last between 10 ms and 3 sec.

Power quality problems may affect sensitive loads. The following main power quality problems are defined and briefly discussed.

- *Voltage sags* are short duration reductions in rms voltage (0.1 pu to 0.9 pu) of 0.5 cycles to 1 min [49] as a consequence of faults, or starting of large motors and overloads. Voltage sags have the potential to disrupt sensitive load operation and cause loss of production [40].
- *Voltage swells* are increases (1.1 pu to 1.8 pu) in rms voltage of duration from 0.5 cycle to 1 min. The main reasons for voltage swells are the switching of large capacitors, removal of large loads or grid faults. For instance, a single-line-to-ground fault on an un-grounded 3-phase system may cause a voltage swell on the healthy phases.
- *Over-voltage*: A voltage magnitude above the normal operating voltage range for duration of more than 1 min [40, 49]. Typical over-voltage values are 1.1 to 1.2 pu. Over-voltage events with duration less than one minute are categorized as voltage swells.
- *Short interruptions*: The complete loss of voltage (< 0.1 pu) on one or more phases for a period between 0.5 cycles to 3 sec [49]. The causes of short interruptions are fault clearing by a protection system, incorrect protection intervention, among other causes.
- *Phase angle jump*: The displacement in time of one waveform with respect to another of the same frequency and harmonic contents [49]. Some loads such as thyristor-based drives are sensitive to phase angle jump where it can lead to wrong zero crossing.
- *Harmonic distortions*: Non-sinusoidal voltage waveform distortion caused by harmonic contamination but periodic with a period equal to integer multiple of

the power system frequency (50 or 60 Hz) [40].

- *Voltage Flicker*: The fast changes in voltage magnitude are referred to as voltage flickers. They may result in the sensing of unsteadiness in light intensity of lamps. The frequency of these disturbances could be from 1 to 10 Hz [4]. The amount of flicker can be measured in term of flicker severity denoted as P_{st} .

There are other power quality disturbances such as voltage and/or current transients, voltage unbalance, under-voltage, noise, voltage/current notch, power frequency variations, in addition to the above mentioned power quality disturbances.

According to the surveys, voltage sags are one of the most common and serious problems that may affect customer devices. Some examples of the affected equipment are programmable logic controllers (PLCs), switched-mode power supplies, adjustable speed drives, electromechanical relays and contactors [40, 50].

In the next section, some conventional voltage sag/ swell mitigation methods will be described.

2.2. Conventional Techniques for Mitigating the Impacts of Voltage Sags and Swells

There are various approaches to mitigate the impacts of voltage sags/swells, some of which are listed as follows [40]:

- i. Reduce the number of fault occurrences.
- ii. Reduce the fault clearing time.
- iii. Improve power system design.
- iv. Improve the immunity of equipment against disturbances.
- v. Connect mitigating device between power-quality sensitive load and the supply.

Measures (i) – (iii) and (v) are performed at network level whereas (iv) depends on the manufacture of the sensitive electrical equipment.

In this research, the focus is only on the design of mitigation device(s) for use to improve voltage quality. In this aspect, specific techniques have been proposed in the literature and most of them are based on the injection of active and reactive powers to compensate for the loss of active and reactive powers supplied by the system. In recent years, attention has been directed toward the use of power electronic devices for power quality enhancement. These are called Custom Power devices and they can be classified according to the topology used: shunt [51-69], series [68, 70-97] and combination of series and shunt connections [68, 98-110]. In the following subsection, previous research works on the devices will be explained.

2.2.1. Shunt Voltage Compensator

One of the earliest attempts to improve power quality is through the use of shunt-connected voltage compensator. A generic diagram showing how such a compensator is incorporated into grid is shown in Fig. 2.1(a). The compensator can be seen as a current source which is connected in shunt with the distribution system and the load. The injected active and reactive powers (i.e. P_i and Q_i) shown in the Fig. 2.1(a) can be controlled by adjusting the magnitude and the phase angle of the output voltage of voltage sourced converter (VSC). A good example of such a device is the Static Compensator (STATCOM). It is a shunt-connected Flexible AC Transmission System (FACTS) device which can inject only reactive power designed to mitigate power quality issues such as poor power factor of load, reducing harmonic contents, unbalance load current and compensation of voltage dips/swells. Since the STATCOM only injects reactive power to the system, the injected current phasor $\bar{I}_i$ is in quadrant with the load voltage phasor $\bar{V}_L$.

There have been a large number of publications on STATCOM reported in the literature. For example, single-phase pulse width modulation (PWM) voltage source inverters are used in STATCOM described in [51-53]. Three-phase 3-wire STATCOM is presented in [54-57, 60, 62, 63, 65-67]. In order to reduce adverse impact of single-phase loads including unbalance voltage, harmonics, reactive power load and neutral current, various forms of 4-wire Distributed-STATCOM (DSTATCOM) are described in [58, 59, 61, 64]. DSTATCOM is the most widely

used Custom Power device connected into distribution systems. In this way, small voltage variation can be mitigated using STATCOM [69] but the mitigation of deep voltage sag requires the injection of active power as well. The ability to control the fundamental load voltage depends on the effective impedance to the supply system and the power factor of the load. In the case of low supply impedance, mitigation of voltage sag is very difficult to achieve by shunt-connected reactive current injection method because the injected current has to be very high in order to maintain the load voltage.

Fig. 2.1 (a) Shunt Voltage Compensation (b) Series Voltage Compensation.

2.2.2. Series Voltage Compensator

In series-voltage compensation, usually a VSC is used to inject active and reactive power. The compensator is connected in series with the load and the grid supply. Fig 2.1(b) shows a generic diagram of series compensator. Clearly the load voltage $\bar{V}_L$ is equal to the sum of the series injected voltage $\bar{V}_i$ and the grid supply voltage $\bar{V}_s$. A transformer is usually used at the output of the VSC to step up the voltage and also provides electrical isolation. The series compensator can control P_i and Q_i by controlling the injected voltage magnitude and phase angle to restore the load voltage V_L during voltage disturbances. The required energy for active power injected is provided by the energy storage at the dc terminal of VSC as shown in Fig. 2.1(b).

Dynamic Voltage Restorer (DVR) is a well-known series-connected compensator which has been shown to mitigate the voltage dips and swells most effectively [68, 70-97].

In the case of the DVR, three basic control strategies can be stated as [111]:

- Method 1, Pre-sag compensation: the DVR tracks the supply voltage continuously and the load voltage is restored to the pre-disturbance condition. The method gives a nearly undisturbed load voltage in the face of grid voltage phase angle jump. Fig. 2.2(a) shows the phasor diagram of the pre-sag compensation method.
- Method 2, In-phase compensation: the injected voltage is always in phase with the supply voltage regardless of the load current and the pre-disturbance voltage. Fig. 2.2(b) shows the phasor diagram of the in-phase compensation technique.
- Method 3, Energy optimal compensation: DVR generates voltage to mitigate voltage sag. The load current is adjusted to minimize the depletion of the stored energy by adjusting the injected voltage phasor $\bar{V}_i$. When the injected voltage and the load current phasors are perpendicular to each other, the injected active power is zero. The phasor diagram of the energy optimal compensation method is shown in Fig. 2.2(c).

Fig. 2.2 Phasor diagram of sag compensation methods (a) Pre-sag compensation (b) in-phase compensation (c) Energy optimal compensation.

All the compensation methods need to inject certain amount of active power to the loads during voltage sag most of the time. However, using the energy optimized Method 3 will reduce the required capacity of the ESS within the DVR, compared to that based on Methods 1 and 2.

The main topologies of DVR can be categorized into two groups, as follows:

- **With an AC/DC/AC conversion stage:** In this topology, the required energy is provided from a shunt converter connected to the supply or to the load side [90, 97]. The main drawback of this type of DVR with no energy storage is that this system will draw increased level of current from the grid during fault and causes

Fig. 2.3 (a) DVR with no energy storage and supply-side-connected AC/DC converter, (b) DVR with no energy storage and load-side-connected AC/DC converter, (c) DVR with energy storage.

further voltage drop at the load terminal [90]. Fig. 2.3(a) shows the DVR with supply-side-connected AC/DC converter and Fig. 2.3(b) shows the DVR with load-side- connected AC/DC converter.

- **With an energy storage device:** In this group of series compensators, the required energy is taken from an energy storage device. Fig. 2.3(c) shows the DVR with an ESS. Constant and variable DC link strategies are commonly used. DC-link energy storage in the case of variable DC link voltage strategy may be recharged by the series converter or by a low-capacity auxiliary charging converter when the grid is in normal operation. In constant DC-link voltage systems, direct energy storage methods such as super-conducting magnetic energy storage (SMES), batteries or super-capacitors can be used. The overall capacity of the converter in variable DC-link voltage is less than that based on the constant DC voltage strategy [90]. Since the cost of the energy storage system (ESS) is a significant part of the total cost of the DVR, thus much research has been done to reduce the capacity of energy storage devices required to mitigate sags/swells [78, 95, 112]. In order to charge the ESS, different sources can be utilized. In [96, 113], the authors have proposed connecting rectifier charger to the grid as an alternative way to charge the ESS while in [80, 95], the inverter of the series compensator can recharge the ESS from the grid without using any additional hardware [80, 95]. The latter is a more cost-effective solution because it does not need an additional charger. The series compensator can be fed from an active DG source [114] if a DG with suitable power rating is available.

With the means of an appropriate control system, the topology also lends itself to recharging the capacitors to their nominal voltages in a straightforward manner.

It is well-known that series compensation requires less injected power to achieve voltage control, as compared with shunt compensation for a stiff grid system. Thus the capacity of the series-connected power conditioner is smaller than that of the shunt-connected compensator in strong ac systems [115]. The main limitation of the shunt compensator is that as the source impedance becomes increasingly smaller,

maintaining the terminal voltage of the shunt compensator becomes less and less practical because of the increasingly large current and high active power demand required [40, 56, 116].

Series compensator also can mitigate some power quality originated from the load side. For example, the series compensator can provide good attenuation against distortions caused by nonlinear load: the harmonic distortions can be reduced if the appropriate harmonic rejection control is incorporated to the series compensator controller. Interested readers can refer to [88, 116-118] for more details.

2.2.3. Analysis

The simplified single-line circuit diagram of the series and shunt compensators are shown in Fig. 2.4. The diagram could be used to analyze the steady-state performance of series and shunt compensators when mitigating upstream voltage disturbances. The upstream equivalent grid impedance is Z_S . E_S is the open-circuit voltage of the equivalent grid source. $\bar{V}_L$, $\bar{I}_L$ and φ denote load voltage phasor, load current phasor, and load power factor angle. $\bar{V}_L$ is assumed as a reference, thus $\bar{I}_L = I_L \angle -\varphi$. $\bar{V}_I = V_i \angle \alpha$ denotes the series injected voltage whereas $\bar{I}_i = I_i \angle \lambda$ represents the shunt injected current.

Fig. 2.4 Single-line equivalent circuit representing key parameters of (a) series compensator (b) shunt compensator

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Using the approach presented in [56], the minimum amount of series injected voltage V_i and shunt injected current I_i can be found as follows. The conditions of minimum injected series voltage and shunt injected current correspond to the condition of minimum injected power for the series and shunt compensators respectively.

The series injected voltage shown in Fig. 2.4(a) can be obtained from KVL, hence

$$\bar{V}_i = \bar{V}_L + Z_S \bar{I}_L - \bar{E}_S \quad (2.1)$$

Then from (2.1), one can write

$$V_i \angle \alpha = V_L \angle 0 + Z_S I_L \angle (\beta - \varphi) - E_S \angle \delta \quad (2.2)$$

where α, β, δ are the phase angle of $\bar{V}_i, \bar{Z}_S$ and $\bar{E}_S$ respectively. Equation (2.2) can be rewritten as

$$V_i \angle \alpha = (V_L + Z_S I_L \cos(\beta - \varphi) - E_S \cos(\delta)) + j(Z_S I_L \sin(\beta - \varphi) - E_S \sin(\delta)) \quad (2.3)$$

Thus V_i is determined using (2.3)

$$V_i = \sqrt{(V_L + Z_S I_L \cos(\beta - \varphi) - E_S \cos(\delta))^2 + (Z_S I_L \sin(\beta - \varphi) - E_S \sin(\delta))^2} \quad (2.4)$$

Therefore, the condition of minimum injected voltage of series compensator for given $Z_S, \bar{V}_L, \bar{I}_L$ and $\bar{E}_S$ is

$$\frac{\partial V_i}{\partial \delta} = 0 \quad (2.5)$$

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The solution of (2.5) is given as

$$\delta = \arctan\left(\frac{Z_S I_L \sin(\beta - \varphi)}{V_L + Z_S I_L \cos(\beta - \varphi)}\right) \quad (2.6)$$

For the given load, grid voltage and impedance, δ can be readily calculated using (2.6). The minimum V_i can be obtained by substituting δ into (2.4) and consequently the apparent power of series compensator $V_i I_L$ can be readily determined.

The same approach can be used for shunt compensator; the injected current can be calculated using KCL in Fig. 2.4(b)

$$\bar{I}_i = \bar{I}_L - \bar{I}_S \quad (2.7)$$

As $\bar{I}_S = (\bar{E}_S - \bar{V}_L)/\bar{Z}_S$, (2.7) can be expressed as

$$\bar{I}_i = \bar{I}_L - \frac{(\bar{E}_S - \bar{V}_L)}{\bar{Z}_S} \quad (2.8)$$

$$I_i \angle \lambda = I_L \angle -\varphi - \frac{E_S}{Z_S} \angle (\delta - \beta) + \frac{V_L}{Z_S} \angle -\beta \quad (2.9)$$

or

$$\begin{aligned} \bar{I}_i = & \left(I_L \cos(-\varphi) - \frac{E_S}{Z_S} \cos(\delta - \beta) + \frac{V_L}{Z_S} \cos(-\beta) \right) + \\ & j \left(I_L \sin(-\varphi) - \frac{E_S}{Z_S} \sin(\delta - \beta) + \frac{V_L}{Z_S} \sin(-\beta) \right) \end{aligned} \quad (2.10)$$

The magnitude of the shunt-injected current can be expressed as

$$I_i = \sqrt{\left(I_L \cos(-\varphi) - \frac{E_S}{Z_S} \cos(\delta - \beta) + \frac{V_L}{Z_S} \cos(-\beta) \right)^2 + \left(I_L \sin(-\varphi) - \frac{E_S}{Z_S} \sin(\delta - \beta) + \frac{V_L}{Z_S} \sin(-\beta) \right)^2} \quad (2.11)$$

The condition for minimum injected current is

$$\frac{\partial I_i}{\partial \delta} = 0 \quad (2.12)$$

To satisfy equation (2.12), δ can be shown to be

$$\delta = \arctan\left(\frac{Z_S I_L \sin(\beta - \varphi)}{V_L + Z_S I_L \cos(\beta - \varphi)} \right) \quad (2.13)$$

Hence the condition of minimum injected shunt power can be determined by finding the corresponding δ using (2.13), for the given load, $\bar{E}_S$ and $\bar{Z}_S$. Then the minimum I_i and minimum apparent power rating of the shunt compensator $V_L I_i$ can be obtained for the known δ . The detailed derivation of (2.13) is presented in Appendix B.

To demonstrate the effectiveness of the series compensator, an illustrating example shall be used herewith. Assume the load is 1.0 p.u. at 0.8 lagging power factor. The source equivalent impedance could change from 0.01 to 0.1 p.u and its resistance component is negligible. The source voltage varies from 0.1 to 0.9 p.u. to represent different sag condition. Also it is assumed that the voltage magnitude of the load bus is to be maintained at 1.0 p.u. under the assumed sags. Minimum power ratings of the series and shunt power conditioners are calculated and illustrated in Fig. 2.5 for the various source impedances and source voltages using (2.4), (2.6), (2.11) and (2.13).

For instance in the case of $E_S = 0.3$ p.u. and $X_S = 0.01$ p.u., the minimum required series compensator rating is about 0.7 p.u. but in the case of shunt compensator, the

minimum required power rating of compensator is some 30 p.u. which is completely impractical. As can be observed from the curves, the power ratings depend highly on the source impedance. The shunt device rating is significantly greater than the series device for the case of small grid impedance (i.e. strong power system): the required capacity of the series power converter is much smaller than that of the shunt compensator under the condition of stiff upstream grid system.

Fig. 2.5 Power rating of compensator versus source impedance for different source voltage: (a) series compensation, (b) shunt compensation

Thus from the above analysis, one can conclude that a series compensator is much more effective than a shunt compensator of the same rating in maintaining load voltage due to upstream voltage disturbance. This is the underlying principle why a series compensator such as a DVR is cost-effective and can mitigate most voltage sags in stiff grid system. It is also the reason why various topologies of the DVR has been reported in the literature: DVR topology without the series injection transformer [77], DVR inverter with reduced count of power electronic switches [87, 89] and

DVR without the utilization of ESS [91, 95]. Furthermore, single-phase DVRs have been reported in [51, 52, 79, 87, 91], while 3-phase, 3-wires DVRs have been reported in [70, 71, 75, 77, 78, 82-85, 92, 94, 95]. In order to reduce the adverse effect of single-phase load including unbalance voltage, harmonics, reactive power load and neutral current, 4-wire DVRs have also been proposed in [72, 81, 86].

2.2.4. Unified Power Quality Conditioner (UPQC)

A UPQC is used to perform both series and shunt compensations at the same time. Two voltage source inverters (VSIs) are connected to a common DC link capacitor [119, 120]. One of the VSI is connected in series with the AC line and the other is shunt-connected with the line. In a way, the UPQC can be considered as the combination of STATCOM and DVR. UPQC can inject current in shunt and voltage in series simultaneously. The series compensator (inverter I) can mitigate the voltage sags/swell, balances the 3-phase load voltage and reduces the harmonic distortion. Shunt compensator (inverter II) can mitigate distorted load current and achieve unity input power factor. Furthermore inverter II maintains the DC-link voltage at constant level. Fig. 2.6 shows the single-line diagram of the UPQC.

Fig. 2.6 Simplified single-line diagram of UPQC

Fig. 2.7 depicts the phasor diagram of the various quantities in the UPQC under sag condition. One can see from the figure that the series injected voltage $\bar{V}_i$ is added to

the source voltage $\bar{V}_S$ such that the device can eliminate voltage sag and maintain the load voltage $\bar{V}_L$ at constant magnitude. UPQC injects series voltage such that when the series compensator does not inject any active power, $\bar{V}_i$ is in quadrature with the current $\bar{I}_S$ which flows through the series compensator. The shunt injected current $\bar{I}_i$ from the shunt inverter achieves unity power factor by supplying the load reactive power and making the source current $\bar{I}_S$ in-phase with $\bar{E}_S$.

Fig. 2.7 Phasor diagram of UPQC under sag condition.

The main disadvantages of UPQC are the complex control scheme and the high cost of the installation.

2.2.5. Other Custom Power Devices

Researchers and manufacturers have proposed other devices to mitigate the momentary disturbances, some of which are briefly explained as follows.

2.2.5.1. Uninterruptable Power Supply (UPS)

An UPS could be described as a cascade-connected power quality conditioner. During normal operation, the UPS draws its power from the upstream power supply, converts the AC voltage to DC and then inverts the DC to AC with constant required frequency and magnitude. During voltage disturbance, the energy required by the load is

supplied from the internal battery of the UPS. The load voltage can be kept constant during voltage sag or during supply interruption [40]. Fig. 2.8 shows the a typical configuration of an UPS system.

The advantage of UPS is its simple operation and control. UPS can mitigate most of voltage sags and short interruptions if the ESS (normally in the form of batteries) with sufficient energy is available. The main disadvantage of UPS is the power loss due to additional conversions of the AC-DC and DC-AC stages, and in the battery ESS during normal condition. Also batteries need maintenance and periodical tests to ensure reliable operation when needed during voltage disturbance events. The apparent power rating of UPS should be at least equal to load rated power. Therefore UPS has high cost per kW and high losses.

Fig. 2.8 Typical configuration of an UPS.

2.2.5.2. Static Transfer Switch (STS)

Static transfer switch (STS) transfers the power supply of the load from the abnormal supply to alternative healthy supply within a few milliseconds in the case of any fault at the primary side. This is feasible only at places where there is more than one incoming-supply and these supplies must be from different substations. So the costs

associated with dual supplies could be significant [121, 122]. Fig. 2.9 shows the typical configuration of STS. Often the STS is power-electronics based.

Fig. 2.9 Typical configuration of static transfer switch.

2.2.5.3. Static Voltage Boosters (SVB)

The SVB consists of a serial booster transformer fed through two back-to-back connected thyristors to regulate voltage. By controlling the firing angle of thyristors, the output voltage of the SVB can be compensated [123]. Fig.2.10 shows the single-line diagram of a SVB. The bypass switch opens when an upstream sag is detected.

2.2.5.4. Solid state Current limiter (SSCL)

Basic SSCL includes a bidirectional solid state switch (e.g. two anti-parallel gate turnoff thyristor in parallel) with limiting current inductor which is parallel-connected with a snubber [124]. As shown in Fig. 2.11, the SSCL is connected in series with a feeder such that it can limit the downstream fault current. In the normal condition, the bidirectional switch is conducting. During fault condition, it opens and current flows through the current limiting inductor. Thus the fault current will be limited as the limiting impedance is now in series with the load. Other SSCL

topologies have also been presented in [125, 126] where the intention is to reduce the capacity of the static switch and to improve the efficiency of the SSCL.

There are other types of device to mitigate voltage sags such as ferro-resonant transformer, motor-generator set and electronic tap changer. As the underlying principles governing the operation of these devices are outside the scope of this research, they shall not be further discussed in this thesis. Interested readers may wish to refer to [40].

Fig. 2.10 Single-line diagram of a static voltage booster.

Fig. 2.11 Typical configuration of solid state current limiter.

2.3. Impacts of DRGs on Power Quality

Having briefly explained the various mitigation devices that can be used to enhance power quality, attention is now turned to the integration of distributed renewable generators (DRG) into grid systems and how DRG could also impact power quality, including that on voltage fluctuations, harmonic and unbalance.

The reason why DRG is considered is because since the deregulation of the electricity market, the penetration of DRG into grid systems has grown significantly. Consequently, the impacts of DRG are shifting from that of the transmission to distribution level and cover a wider area of the grids. In a weak transmission network, disturbances originated from the many DRG can have adverse impact on the grids.

DRGs, particularly those without any ESS to act as energy buffers, are considered non-dispatchable distributed generators (DG) because of the often intermittent behavior of renewable energy sources such as solar and wind. Non-dispatchable DGs may cause voltage fluctuation on low voltage buses because of the fluctuations in the generated power. Another important voltage quality issues that can be impacted by high penetration of DRGs is voltage dips. Furthermore due to the presence of the large number of single-phase DRGs in low-voltage residential or commercial load areas, distribution systems may experience un-acceptable level of voltage and current unbalances. On the other hand, the appearance of 3-phase DRGs tends to increase the short-circuit current level of the distribution grid. The stiffer network will help to reduce the voltage imbalance. More detail can be found in [4].

While DRGs with power-electronic interfaces can act as harmonics sources, their contributions to grid harmonics distortion tend to be less than that due to nonlinear loads. Besides, by including some ancillary functionalities, such as active power filtering, into the power-electronic-based DRGs may also help to reduce the harmonic contents of the grid voltage.

As the main focus of this thesis is on the mitigation of voltage sags using DRGs and to reduce voltage fluctuation induced by the intermittent renewable sources, these aspects of the inter-relationship between power quality and DRG shall be discussed in the following sections.

2.3.1. Voltage Fluctuations Due To Unsteady Renewable Generation

Voltage fluctuations are fast changes in voltage magnitude. They are usually continuous and their time scale is in the range of seconds to several minutes. The fluctuations in the power generated by the intermittent DRG could in turn lead to voltage fluctuations. In the following, power fluctuations of two main renewable sources will be described.

a. Fluctuations in solar power

Passing cloud or other objects in front of PV panel will result in irradiation changes and consequently, will affect the output of the PV arrays. The scale time of these fluctuations is in the range of seconds. For a single PV system, 75% reduction of the nominal power can happen due to irradiance change within about 7.5 seconds (i.e. 10% power reduction per second) [4]. Also according to field measurements, direct irradiance could decrease by about 900 W/m^2 in about 6 sec [127]. The number of high irradiance change (i.e. change of more than 400 W/m^2) per year has been reported to occur about 460 times in a year [4]. Hence, the changes are not negligible. Furthermore, PV modules are usually connected in series to match the designed operating voltage level of the PV inverter. If one module in the array is shaded, the impact on the output power of PV array is more than the size of the part that is shaded [4]. For example in an array with 24 identical series-connected cells, even one shaded cell can reduce about 50 % of the total power [128]. Impacts of PV power variations on flicker severity were reported in [129], and the authors have shown that correlation between the amount of power injection level and flicker severity in some cases. Therefore irradiance changes and partial shading of the PV modules are the main reason of power fluctuation at the output terminals of PV generators.

b. Fluctuations in wind power

Wind power generation varies due to variation of wind speed, turbine dynamic, gearbox change, tower resonance and periodic rotation of blades with respect to tower [130, 131]. Frequency of fluctuations related to blades passing is proportional to the number of blades. Measurements show that the fluctuation corresponding to the gear box rotation speed and tower resonance are about 2.5 Hz and 1.1 Hz respectively [132]. Flicker contributed from wind energy conversion system has been studied through simulation or measurement and presented in [132-137]. According to these studies, typically the contribution of wind power on flicker level severity (P_{st}) is about 0.2 if the short circuit level at the wind generator connection point is between 7 and 25.

Thus as explained above, among many causes, fluctuation in the PV power caused by moving clouds and wind speed variation may lead to large variations in the generated power. This will in turn result in unacceptable voltage quality in the connected grid systems. This issue can be explained as follows.

2.3.2. Analysis of the Impact of Fluctuating Renewable Power on Voltage

Fig. 2.12 shows a DRG inter-connected to a grid at the point of common coupling (PCC). The voltage phasor at the PCC is denoted as $\bar{V}_S = V_S \angle \theta$. As the external system connected to the DRG is complex, a Thevenin equivalent model is used to represent the grid. The voltage source E_S equals to the no-load voltage at the PCC. The electrical strength of the grid can be related to the source impedance Z_S . The focus of attention is on the voltage quality at the PCC when the DRG injects into the grid the complex power $P_i + jQ_i$.

With the DRG injecting $S_i = P_i + jQ_i$ into the grid, the voltage at the PCC will deviate from E_S . If E_S is the reference voltage and without any loss of generality, it is set as 1 p.u., then the voltage deviation ΔV at the PCC with respect to E_S can be expressed as

$$\Delta V = V_S - E_S \quad (2.14)$$

$$\Delta V = \frac{R_S P_i + X_S Q_i}{V_S} \quad (2.15)$$

Fig. 2.12 Schematic diagram of a DRG connected to grid.

The derivation of (2.15) is well-known and it governs the steady-state value of the voltage variation [138]. Also it is assumed over the interval of interest, any voltage control device in the network has not been initiated as to cause any changes to the grid impedance (Z_S) and E_S . Therefore in this derivation, E_S and Z_S are assumed constant. In this way, the impact of the DRG output power on the PCC voltage quality could be readily assessed via (2.15).

Z_S and S_i are two important factors that can impact the amount of ΔV . In constant power factor operation mode, Q_i is proportional to P_i and as can be seen from (2.15), any deviations of S_i will induce voltage changes at the PCC. It should be noted that the voltage changes increases with $R_S + jX_S$ for an inductive grid system.

In order to reduce the negative impact due to solar power variations, four different techniques have been proposed in the literature. These methods are

- Using battery energy storage systems
- Using dump loads: The dump load includes a resistance bank and a power flow control unit.

- Restricting the generated power below the maximum power point (MPP): This method does not require any additional hardware installation.
- Adjusting the output reactive power of the PV inverter.

Omran et al [26] have studied the first three techniques for large-scale PV systems. Their results show that irrespective of the method implemented, there is a loss of revenues as compared to the case when no power smoothing techniques is utilized. Not surprisingly, it was observed that by imposing stricter voltage fluctuation limit, the loss in revenues increases because lower setting of voltage fluctuation will increase the power and energy capacity of the batteries. According to the study, if a larger power fluctuation is allowed, utilizing dump load and power curtailment below MPP are more beneficial compared to the use of battery storage. Adopting the combination of battery energy storage and power reduction is the best economical solution among these three methods.

In order to curtail the power fluctuation with high-frequency occurrence (in the range of seconds to an hour), conventional battery energy storage would not be a suitable solution. Other types of energy storage such as supercapacitor and superconducting magnetic energy storage are alternative solutions. Only up to a few years ago, the capacity of these ESS were limited and they were only able to bridge the fluctuation for 1-2 min [139, 140]. However due to capacity improvement, these ESS can now curtail power fluctuations of half an hour or longer duration [141, 142].

Hybrid energy storage including super-capacitor and battery would be the other possible solutions to reduce the voltage fluctuation introduced by the DRGs and achieve power dispatchability. In this approach, the rate of charging/discharging powers of the battery and super-capacitors are controlled: low-frequency components of the harnessed power are to be diverted to the battery because the battery is unable to deal with the high-frequency power fluctuations, and faster power transients are directed to the super-capacitor. This solution will enhance the battery lifetime [143-145]. Thus hybrid ESS would be a promising storage for buffering power in PV systems because the range of fluctuations in PV system is in the range of few

seconds and up to one hour. However, further investigation is required to reduce the cost of hybrid ESS in residential and commercial applications.

Another cost-effective solution is using variable reactive power [28-33]. As it can be seen from the numerator (2.15), Q_i can be controlled properly in such a way that ΔV becomes minimum or even zero. This method is a promising option in mostly inductive grid. This solution is, however, not very successful in highly resistive grid such as a cable-dominated grid. Hence other mitigation technique such as ESS must be utilized because the voltage compensation requires active power injection. Using transformers with static on-load tap-changer could be an alternative solution to mitigate voltage fluctuations. However due to the high cost of its implementation, it would not be a commercially viable product in the near future [146, 147].

2.3.3. Impact of DRG on the Number and Duration of Voltage Sags/Dips in Distribution System

DRGs do not have significant direct impact in the number of voltage sags but the interconnection of large number of DRG to the distribution grid will increase the fault level of the distribution system and thus reduces the magnitude of the voltage change seen by the loads [4]. The majority of commercial and residential loads are connected to medium or low voltage distribution grids. These loads are usually far from large power generation station and an increase in amount of DRG close to these loads will experience a reduction of voltage sag. Hence, a lower sag frequency is observed [148].

On the other hand, grid-connected DRG with electrical machine interfaces can impact the number of voltage sags. For example, during the energization of wind turbine which is coupled to an induction generator, there shall be a large reactive inrush current which can cause voltage sag/dip. The use of soft starting techniques for large induction machines can constrain the voltage dip somewhat. Furthermore, during the voltage dips in the grid, doubly-fed induction generators usually becomes an induction motor and it can draw up to several per unit reactive power which then pulls down the voltage drastically. In contrast, wind generator of the synchronous

machine type would cause a much reduced level of voltage sag and frequency [4, 148]. Majority of power-electronic based DRGs cannot contribute to the fault level during voltage dips in order not to exceed the rating of the converters. Thus in most voltage sag studies, the contribution of power converter-based DRG is assumed negligible [148]. Notwithstanding this, recent grid codes recommend that power-electronic based DRGs should support the grid by injecting reactive power, as in the case of conventional synchronous generators. This reactive power support feature will be considered in greater detail in the next section.

Finally, increasing the number of DRGs in a distribution system may result in longer voltage sags due to longer operation time of overcurrent relays in the distribution network. Furthermore, after fault clearance and considering the fact that re-accelerating the wind generator would draw large amount of reactive current, it can only prolong the duration of the voltage sag, especially in a weak power system [4].

As it can be seen from the above, the impacts of DRG on the frequency of voltage sag are mostly due to un-intentional disturbances. As the main focus in this thesis is on the use of PV power DRG, the utilization of PV generators in low-voltage ride-through (LVRT) will be discussed in greater details.

2.4. Low Voltage Ride Through Capability and Power Quality Enhancement Using Distributed PV Generators

Common strategy to interconnect photovoltaic power inverters to the grid is based on shunt connections. A number of shunt grid-tied PV generators have been presented in the literature [12, 13, 15, 23-25, 31, 149-163]. Fig. 2.13 depicts a typical configuration of a single-phase PV inverter which is able to control active and reactive powers.

Indeed in recent years, much investigations have been performed on integrating PV systems which have extra functionalities such as power quality conditioning [13, 15, 23-25, 31, 153, 154]. In [13], design of a single-phase shunt PV inverter has been presented. This inverter utilizes a repetitive controller to regulate the voltage. The

proposed inverter is able to provide grid voltage support at the PCC and also harmonic distortion compensation. The inverter could mitigate the voltage distortion such as sag/swell by controlling the active and reactive powers when the sun is available and it could compensate small voltage sags. Under low solar irradiance condition, the inverter can compensate just reactive power and filters the harmonics distortions. The main drawback of the proposed system is due to the introduction of an inductance to make the grid mostly inductive and the performance of voltage sag mitigation is only effective in mitigating the impacts of shallow voltage dips, as a consequence of shunt connection of the PV inverter.

Fig. 2.13 Typical control diagram of a single phase grid-connected PV system.

In [23], the design of a grid-connected PV inverter has been proposed to generate power as well as power quality improvement. Voltage vector oriented reference frame models were used to control the inverter. The current and voltage control loops were designed using PI compensators. The inverter could realize harmonic elimination and shallow voltage sag/swell compensation. The system employed battery energy storage and during low sun condition or voltage sags, it can provide additional active power by discharging the batteries. Using the battery ESS requires

additional DC/DC converter and it increases the cost of implementation. A half-bridge single-phase two-wire PV inverter is presented in [24] which can provide active power filtering and active power injection. In [25], a grid-tied PV inverter with active power filtering functionality was studied. Due to limited inverter rating and high harmonic distortion in the grid, the amplitude limiting control method is realized to attain the harmonic and reactive power compensation. Using two active switches, it would be a cost effective solution but it needs higher input DC voltage as compared to full-bridge converters. Rahmani et al [15] proposed a grid-tied PV inverter which is capable of managing PV power generation, and compensating the harmonics, reactive power as well as unbalance voltage. In order to charge and discharge a battery energy storage system, a bidirectional buck/boost converter has been used. To avoid passive filter usage that can slow down the dynamic response of the inverter, a nonlinear control scheme was adopted. Integration of active power filtering and PV power generation has been reported in [153], [154]. These PV generators could operate as a shunt active power filter in order to improve power quality as well as enable power generation. The active power filter is utilized to provide harmonics distortions compensation and power factor correction.

As mitigation of the impacts of voltage sags/dips has become an important consideration, a voltage control scheme has been proposed in [12] to provide low voltage ride through (LVRT) capability for a three-phase grid connected inverter within the limits established by grid codes. The current control scheme presented in [164] has been used to adjust the reactive power reference and the variable ratio between the positive and negative sequence reactive currents. In order to regulate the PCC voltage during voltage dips in the three-phase systems, the DRGs inject reactive power according to positive sequence voltage of PCC but in the case of unbalance sags, this method can only raise the positive sequence voltage and the negative sequence voltage is still unchanged. Thus it may lead to inadmissible voltage on the healthy phases. More recently, research works have been presented using both the positive and negative sequence voltages for adjusting the amount of injected reactive power [12, 21, 155, 156, 164-167]. When a fault occurs, it is required that PV

generators should be able to supply the local loads regardless of grid condition [35, 37]. This is known as an anti-islanding protection [163]. An unexpected PV generators outage in an unintentional operation of anti-islanding protection may result in more severe issues than the initial event [163].

In the next subsection, the ability of PV generators to provide load LVRT will be discussed.

2.4.1. LVRT Capability Pertaining to Shunt-connected PV Generator

Most of small scale grid-connected PV generators are installed in residential grids. According to conventional grid regulations, if a grid fault occurs and within a certain time, these PV systems should be disconnected from the grid [168]. If there is high penetration of these single-phase PV generators and if they are suddenly disconnected following a fault occurrence, it may amplify the adverse effect of the fault because the sudden loss of a significant portion of power production may lead to severe voltage change, and even threaten grid stability [169-173]. Nonetheless, if the PV inverter equipped with some ancillary functions such as LVRT and reactive power adjustment, then these events may be avoided [174-178]. Thus in this way, the next generation of PV DRG should provide grid support similar to conventional power plant. Indeed, industrialized countries such as Japan [175, 176], Germany [37] and Italy [179] have updated their grid standards [163] to reflect this requirement. For example in Italy, the generation units with rated power above 6 kW should have LVRT capability under grid faults.

Regarding the topology of single-phase PV generator (PVG), different isolated and non-isolated (transformerless) topologies have been proposed [149]. Due to higher efficiency of transformerless inverter of PVG, these inverters have been studied in recent years [180], [157] - [162]. Yongheng et al have explored three most promising conventional single-phase transformerless PV inverters, including full-bridge inverter with DC bypass (FB-DCBP), highly efficient and reliable inverter concept (HERIC) and FB inverter with bipolar modulation (FB-Bipolar) [163]. The authors evaluated the inverters in terms of efficiency, LVRT capability and leakage current

rejection. One can conclude that HERIC is not suitable for LVRT due to severe grid current distortion at voltage zero crossing points, even though its efficiency is higher than others. The performance of FB-DCBP and FB-Bipolar are acceptable during LVRT. The efficiency FB-DCBP is slightly higher than that of the FB-Bipolar inverter but under LVRT operation mode, this inverter experiences significant high level of common mode voltage (high leakage current). Furthermore high current stress on extra switches of FB-DCBP may introduce device failure. FB-Bipolar inverter can ride through the grid fault in a wide range of voltage dips by providing the reactive power injection and also FB-DCBP is able to mitigate voltage sag in the range of 0.5-0.9 p.u. [163].

Controllers designed to effect current loop control in single-phase shunt-connected PV inverters in grid systems are [163]:

- a. Proportional resonant
- b. Resonant control
- c. Repetitive controller
- d. Deadbeat controller
- e. Proportional integral controller

2.4.2. LVRT Capability Pertaining to Series-connected PV Generators

All of the proposed methods in the previous sub-section are shunt-connected. Another solution to connect PV to grid is through series connection. In Section 2.2.3, the advantages and disadvantages of series and shunt compensators were discussed. The main limitation of the shunt compensator is that when the source impedance becomes small, mitigation of sags is impractical due to very large current and high active power required to achieve compensation. Therefore if a series-connected inverter has been used to improve voltage quality, the capacity of the inverter is smaller than that of the corresponding shunt-connected system. Obviously the series compensator is more cost effective.

Using series-connected PV system for power quality improvement is a rather new concept and there are very few published works in the open literature. In [181], Fei et al proposed the series-configuration of PV inverter equipped with bidirectional switches. Solar energy is fed into the load during day time. In this system, voltage sag can be compensated by in-phase voltage injection and voltage swells can be mitigated by out-of-phase voltage injection. Voltage compensation using this scheme ranges 0-10% of grid voltage. During nighttime, the system can operate by absorbing energy from the grid and inverter can operate as a AC/AC converter [181]. The first drawback of this configuration is that as this system does not utilize energy storage element, during nighttime if a severe voltage dip occurs, then the PVG would draw more current from the grid in order to compensate for the voltage dip. This will exacerbate the voltage dip at the load terminal. This design can only mitigate shallow sags. Also, the use of the in-phase compensation method does not permit the harnessed solar power to be transferred to load under healthy grid condition while during sag/swell incidents, there is no control on the active power flows [14].

Dasgupta et al proposed a daytime control strategy for series PVG [182]. In this strategy, it is assumed that the voltage of the DC-link is constant and the storage device is not utilized between the DC-DC converter and the inverter. An adaptive proportional resonant controller is used. During sag, the load power is partially drawn from the PV system and the rest of the load power is to be supplied by the grid. To facilitate the power flow control, load voltage is forced to have a leading phase relationship with the grid fundamental voltage and the magnitude of load voltage is maintained constant. The authors of [182] also proposed a spatial iterative learning controller for the series-connected PV inverter to eliminate load voltage harmonics [183]. This control system regulates load voltage during normal grid condition and compensates the voltage as an active power compensator during sags/swells. When the fundamental frequency of the grid varies, as may happen in a micro grid, it may lead to the loss of synchronization of inverter voltage with the grid voltage. Thus this solution has been presented to solve the tracking problem of sinusoidal voltage in a grid which is contaminated with harmonics. However, as reported in [184], the

dynamic response of the proposed traditional learning controller is slow. Hence in order to solve this problem, a Lyapunov-function based controller was proposed in [184]. The power circuit and power flow control strategy of the proposed control systems in [183] and [184] are similar to that in [182]. The main drawback of all these proposed control strategies is that the ability to achieve voltage sag compensation reduces with the decrease in the insolation level because the DC-link capacitor is not designed as an ESS in order to provide sufficient active power. All the control strategies in [182-184] have been designed to function well during daytime but they are not suitable during nighttime.

To overcome these difficulties, a PVG with active power flow control is presented in [14] where the authors have incorporated a battery in the DC-link of the generator. However, there is no analysis to demonstrate the need of the battery and on how to determine the required capacity of the energy storage element. Furthermore, in [181], [182-184], the solar irradiation is considered deterministic which is clearly unrealistic. Effect of the stochastic behavior of voltage sag and insolation are not considered in the design of the PVG and the authors have not utilized the potential of an ESS. Probabilistic assessment of series connected PVG is necessary to evaluate the performance of the compensator and this will be elaborated in Section 2.6.

2.5. Grid Code Requirements for PV Power Integration

The continuous increase of PV power penetration into power systems leads to the introduction of various technical grid requirements. Since PV systems are typically connected to low-voltage and/or medium-voltage distributed networks, the grid standards are mainly focused on power quality issues, frequency stability and voltage stability [35]. In this section some of main requirements will be presented.

According to the IEEE standards 1574/IEC 61727, the current THD level must be less than 5%. The DC component of the injected power must be limited to 0.5 % and 1% of rated value, according to the IEEE 1574 and IEC 61727 standards respectively. The voltage unbalance should be limited to 3% [185]. VDE-AR-N 4105

allows the maximum 10 kVA single-phase generator and 4.6 kVA power unbalance in low voltage systems.

Furthermore, the PV generators should provide low voltage ride-through (LVRT) and high voltage ride-through (HVRT) during asymmetrical and symmetrical grid faults. Thus the generator should inject reactive power to support the grid during faults and this may lead to the overloading of the generators' inverters. In order to avoid the overloading, injected active power and reactive power should be limited during grid faults and the recovery period. Furthermore, the duration the DRG should remain connected and contributed toward network recovery should meet the grid requirements. So different LVRT curves have been proposed from utilities and DRGs should comply with these curves. Fig. 2.14 shows LVRT curves of different countries.

Fig. 2.14 Low voltage ride-through requirements of different countries [186] © 2012 IEEE

These LVRT curves governs the level of the voltage sag and duration under which the DRG should stay connected to the grid and support the grid by injecting reactive power during the disturbance. For example, according to the German grid requirement, the DRGs should support the grid for 0.15 seconds when the grid voltage drops to 0. Similarly, voltage magnitude requirement for the LV PV system

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are presented in IEEE 1574 and IEC 61727. The allowed delay for the disconnection of PV system is presented in Table 2.1.

Table 2.1 Voltage magnitude requirement for LV PV system

IEEE 1574	Voltage range (%)	$V < 50$	$50 \leq V \leq 88$	$110 \leq V \leq 120$	$V \geq 120$
	Disconnection Time (sec)	0.16	2.00	1.00	0.16
IEC 61727	Voltage range (%)	$V < 50$	$50 \leq V \leq 85$	$110 \leq V \leq 135$	$V \geq 135$
	Disconnection Time (sec)	0.10	2.00	2.00	0.05

The maximum allowed voltage rise associated with PVG should not exceed to 3% [18]. In countries with high penetration of PV such as Germany and Spain, the voltage of the PVG should not exceed from the voltage limits $0.8V_n \leq V \leq 1.1V_n$ and $0.85V_n \leq V \leq 1.1V_n$ respectively [18]. V_n denotes nominal voltage of the grid. The threshold limits of frequency deviation and disconnection time in LV grid are specified in Table 2.2. After the trip, the PVG should follow standards for reconnection. For instance in IEC 61727, the voltage must be between 85 to 110% of rated voltage, the frequency is between 49 to 51 Hz and the required delay is 3 minutes.

Table 2.2 Frequency deviation and disconnection time in LV grid

IEEE 1574	Frequency range (Hz)	$59.3 < f < 60.5$
	Disconnection Time (sec)	0.16
IEC 61727	Frequency range (Hz)	$49 < f < 51$
	Disconnection Time (sec)	0.20

2.6. Probabilistic Evaluation of PV Power, Load and Voltage Disturbance

As explained in Section 2.3, the output power of PVG may vary significantly for different time of the day due to solar irradiance changes. The load profile of distribution grid is dependent on the season and the day of the week. Furthermore voltage dips can occur in the grid due to unforeseen incidents or unplanned operations such as grid faults. Thus these parameters can be treated in the form of random variables instead of deterministic variables.

In order to design a PVG which is capable of providing LVRT, deterministic method can be used. However, very often the deterministic approach to design the PVG system is referred to as a “worst-case approach” which may lead to an exceedingly over-capacity PVG design. Instead, a more realistic way to design the DRG should be based on a probabilistic analysis because of the random behavior of load, irradiance (or wind) and voltage sag. In this section the random behavior of these parameters will be evaluated in more details. The probabilistic approach to design the PVG will be presented in Chapter 5 and 6.

2.6.1. Stochastic Behavior of Solar Irradiance and Load Demand

Solar irradiance is not easily predictable because it is highly dependent to climatic conditions. The random nature of irregular cloud movement is characterized by global clearness index [187-189] and hourly diffuse fraction [190-193]. These two random variables could make it possible to derive the global irradiance on the surface of a given PV panel in minute or hour intervals using linear combination of incident irradiance beam, diffuse irradiance and ground-reflected irradiance. The generated PV electrical power, as a random variable, is then obtained from the forecasted global irradiation [194]. The uncertainty in solar irradiance and its impact on PV panels could be modeled by the stochastic behavior of the weather condition clearance index as it is adopted to relate to the weather condition and solar irradiance [195].

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It should be noted that load demand and solar irradiation are time dependent random variables. In Fig. 2.15 the daily load and irradiance are presented for two months of 2011 in Singapore [196]. The cyclic change of daily load is apparent from the graph. Also the effect of seasonal load variation is obvious in Fig. 2.15(a) and (b). On the other hand, the power output of the PV system may vary between 20 and 100% from day to day in the daytime. Thus due to stochastic behavior of the irradiance and loads, a probabilistic approach to quantify the effect of the renewable power generation on power quality is necessary.

Fig. 2.15 Daily load and irradiances in the Singapore (a) in April 2011 (b) in December 2011.

At system level studies, for example, a stochastic study is an important part of system dimensioning. From system operation point of view, uncertainty forecasting is required for optimal operation of power systems which have high penetration of stochastic energy sources [197, 198]. Thus these factors lead to the need of multivariable uncertainty analysis of the stochastic variables. The stochastic variables in some cases are highly correlated. For example, the output powers of wind turbines in the same geographical area are tightly correlated or the harnessed power from the sun is correlated to the load demand. For long term planning studies, usually standard distribution such as Weibull or Gaussian may be used for modeling the renewable variables (e.g. wind).

In order to model the time-dependent renewable power sources, the stochastic power is separated to hourly sections and they are modeled as a Gaussian distribution in hourly intervals. This approach is suitable for stochastic modeling of the load demand because, as can be seen in Fig. 2.15 (a) and (b), the load variation is highly dependent of daily and seasonal patterns. Nonetheless, in the case of stochastic generation, time-dependent analysis will not result in a significant reduction of the uncertainty, e.g., the sun irradiance changes can vary at noon from 100% to 20%, depending on the different weather conditions while wind speed can change from 0 to the maximum and vice versa at any time of day/season. The dependency of random variables in time-dependent framework can be modeled by treating them as a linearly correlated Gaussian distribution [199, 200]. Unfortunately dependence modeling using joint normal distribution fails to accurately characterize the dependency when the random variable distributions are non-normal [197]. In order to rectify this problem, a method so-called “copula” is adopted to model dependency of random variables. In the copula method, the random variables are transformed to the rank/uniform domain by applying the cumulative distribution function. The dependence of random variable can be modeled using copula in the rank domain and then the variables are transformed back to the original domain using inverse cumulative distribution function (CDF) [198]. This latter approach is to be described in Chapter 6 of this thesis.

2.6.2. Statistical Analysis of PV Power, Load and Voltage Disturbances

In statistics, empirical probability of an event is the ratio of the number of events occurring to the total number of events. The cumulative density function (CDF) of an arbitrary random variable X having the value of γ is defined as the probability of random variable X which has a value less than or equal to γ

$$prob(X \leq \gamma) = F_X(\gamma) \quad (2.16)$$

where $prob(.)$ is the probability mass function and X takes a value less than or equal to γ . The probability that X lies in the semi-closed interval $(a, b]$, where $a < b$, is therefore

$$prob(a < X \leq b) = F_X(b) - F_X(a) \quad (2.17)$$

For the problem in hand, developing the probabilistic model from measured data of grid voltage disturbances, PV power and load consumption is possible using data acquisition devices and smart meters. Therefore instead of using standard probabilistic distribution or complicated methods, the recorded long term empirical data can be used to develop a stochastic model. A probability distribution function can then be fitted to the empirical data and this distribution would be a non-parametric, non-normal distribution.

The method used to produce the PV output power from empirical recorded irradiance is explained as follows. In PV systems, at a given solar insolation level, there is a unique state at which the maximum power can be extracted from the PV module. This point is called maximum power point (MPP). Typical I-V curve and power output of a PV module are depicted in Fig. 2.16.

Roudriguez et al in [201] presented an analytical solution for determining the MPP in PV systems. Fig. 2.17 shows the photovoltaic cell equivalent circuit. The method is based on knowing the open circuit voltage (V_{OC}) and short circuit current (I_{SC}) of the

Fig. 2.16 I–V curve and power output for a PV module: MPP corresponds to the module delivering the maximum power.

Fig. 2.17 Photovoltaic cell equivalent circuit

PV module. The basic formulae governing v_{pv}^* and i_{pv}^* are shown herewith and more details can be found in [201].

The analytical maximum power point for a module can be calculated from the following equations:

$$v_{pv}^* = \frac{1}{\alpha} \ln \left[\frac{I_{SC}}{\alpha I_S (V_{OC} - r_S I_{SC})} \right] - I_{SC} r_S \quad (2.18)$$

$$i_{pv}^* = I_{SC} \left(1 - \frac{1}{\alpha(V_{OC} - r_S I_{SC})} \right) + I_S \quad (2.19)$$

$$P_{MPP} = v_{pv}^* \cdot i_{pv}^* \quad (2.20)$$

where v_{pv}^* and i_{pv}^* are the voltage and current of the analytic solution of MPP respectively. In (2.18) – (2.20), P_{MPP} is the output power of the PV at MPP; r_S is the series resistance and α is a coefficient where $\alpha = q/n_s kT$; $k = 1.3807 \times 10^{-23} \text{ JK}^{-1}$ is the Boltzmann's constant; $q = 1.6022 \times 10^{-19} \text{ C}$ is the electric charge; T is the operating temperature (in °K); I_S is the reverse saturation current and n_s is the number of series cells in the PV module.

Suppose the solar irradiance recorded in NTU campus is used to calculate P_{MPP} for a particular brand of installed PV module which has the nominal values of $V_{OC} = 18 \text{ V}$ and $I_{SC} = 3.4 \text{ A}$ (at 1000 W/m^2 , 25 °C). It is assumed that the PV panel operates at its maximum power point. The nominal $I_{SC} = 3.4 \text{ A}$ occurs at irradiance 1000 W/m^2 , therefore I_{SC} for other solar irradiances can be calculated based on the ratio of $3.4/1000$. From the measured data, the CDF of the PV power harnessed by the module is shown in Fig 2.18. It can be observed from the figure that the output power of the PV module could be more than 45 W because in some instances in a year, the solar irradiance is more than 1000 W/m^2 .

As for the modeling of loads, empirical load data can be extracted from utility data bank. For this example, Singapore system-wide load data obtained from [196] can be used to illustrate the approach. It is assumed that the statistical distribution of the NTU load is the same as that obtained from [196]. The probability distribution of recorded data can be derived readily using (2.16). The CDF of normalized load power is shown in Fig. 2.19.

Regarding voltage disturbances, some important parameters in sag mitigation studies include the magnitude of voltage sags, duration of the sags and the number of occurrences over a given time. Statistics of these parameters can be obtained from

Fig. 2.18 CDF of photovoltaic power for a 45 W PV panel

Fig. 2.19 CDF of normalized load power.

power quality surveys. Several industry-wide surveys have been reported in the literature. For example: a study carried out by Electrical Power Research Institute (EPRI) involved 277 sites. Monitoring was carried out on distribution feeders and at substations. The results of the survey are shown in Tables 2.3.

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In Table 2.3, a five-minute filter was used whereby all events within 5-minute interval were counted as one event [41].

Table 2.3 Sag events per year for EPRI data with 5 min. filter

Magnitude (p.u.)	0.017-0.1 sec	0.1-0.167 sec	0.167-0.333 sec	0.333-0.5 sec	0.50-1.0 Sec	1.0-2.0 sec	2.0-10.0 sec	10 sec-8 hr
$0.8 < E_S \leq 0.9$	27.6	6.5	3.1	1.4	1.8	0.5	0.4	0.1
$0.7 < E_S \leq 0.8$	8.1	2.2	1.1	0.3	0.5	0.1	0.1	0.0
$0.5 < E_S \leq 0.7$	5.7	1.7	1.1	0.2	0.3	0.1	0.2	0.0
$0.1 < E_S \leq 0.5$	3.5	1.0	0.7	0.3	0.2	0.2	0.6	0.0

From Table 2.3, the number of sag events which have the magnitude between i and j and duration between k and l can be readily obtained. The respective probability of these events is given by

$$prob(i < E_S < j, k \leq t_S \leq l) = \frac{N(i < E_S < j, k \leq t_S \leq l)}{N_S} \quad (2.21)$$

where $N(.,.)$ is the number of sag events which have magnitude between i and j and duration between k and l . N_S denotes the total number of sag events. It should be noted that in the present context, sag events with magnitude less than 0.1 p.u. are assumed as an interruption and they are not counted as sag events. Thus the total number of sag events shown in the table is 69.8. Thus, for instance, $prob(0.8 \leq E_S \leq 0.9 \text{ p.u.}, 0.017 \leq t_S \leq 0.10 \text{ sec}) = 27.6 / 69.8 = 0.3954$. Hence, the probability of all sag events are determined using (2.21) and the data of Table 2.3 yields Table 2.4.

Table 2.4 Probability of voltage sag for given time duration from EPRI study

Magnitude (p.u.)	0.017-0.1 sec	0.1-0.167 sec	0.167-0.333 sec	0.333-0.5 sec	0.50-1.0 Sec	1.0-2.0 sec	2.0-10.0 sec	10 sec-8 hr
$0.8 \leq E_S \leq 0.9$	0.3954	0.0931	0.0444	0.0201	0.0258	0.0072	0.0057	0.0014
$0.7 \leq E_S \leq 0.8$	0.116	0.0315	0.0157	0.0043	0.0072	0.0014	0.0014	0
$0.5 \leq E_S \leq 0.7$	0.0817	0.0244	0.0158	0.0029	0.0043	0.0014	0.0029	0
$0.1 \leq E_S \leq 0.5$	0.0501	0.0143	0.0100	0.0043	0.0029	0.0029	0.0086	0

2.7. Conclusions

In this chapter, a literature review on power quality and related issues has been presented. As power quality surveys showed that the voltage sag is one of the most severe events in distribution systems, various shunt and series mitigation methods to alleviate the negative impact of voltage sags on sensitive load have been reviewed. Due to the wide spread use of intermittent renewable energy sources in distribution grids, the impacts of DRG on power quality degradation are also described and methods to reduce the degradation are included.

In order to eliminate the adverse effect of voltage perturbations caused by the operations of DRGs or due to upstream grid disturbances, some ancillary functions such as LVRT capability should be incorporated into future generation of PVG. Since series compensation is more effective in stiff power system (e.g. Singapore grid) than shunt compensation in enhancing voltage quality, the capability of series-connected PVG to provide load LVRT and to mitigate voltage disturbances is deemed to be higher than the conventional shunt-connected PVG. Thus, in the next chapter, a new series-connected PV generator capable of providing power quality enhancement will be proposed and studied in details.

Chapter 3. A Series-connected Photovoltaic Distributed Generator

3.1. Introduction

In this chapter, a new form of series-connected PV generator (SPVG) system is proposed. The SPVG not only maximizes energy harness during daytime, but also attempts to maintain high voltage quality when upstream voltage disturbances occur or when the input solar power fluctuates. During nighttime or when the input solar energy is insufficient to maintain acceptable level of voltage quality, the stored energy in a capacitor energy storage system (ESS) in the SPVG shall be used to provide the balance of the energy needed to do so. A method to determine the required capacity of the capacitor is presented. Hence during daytime, the SPVG is a renewable distributed generator which exhibits power quality improvement functionality while during periods of low solar insolation or at night, the SPVG operates as a power quality enhancer. Section 3.2 provides a brief description and the design objectives of the SPVG. Section 3.3 contains a detailed analysis on the capability of the SPVG in voltage quality enhancement. The analysis takes into consideration the time-varying input solar power and the rating of the SPVG inverter. The need of the capacitor ESS in the SPVG is demonstrated. Section 3.4 describes a method to determine the required capacity of the capacitor to achieve a given voltage enhancement capability. This is followed by a proposed design of the control scheme of the SPVG in Section 3.5. Simulation results are used in Section 3.6 to illustrate the proposed method.

Some of the materials contained in this chapter also appear in the author's publication [202].

3.2. Preliminary Considerations on SPVG Design

Fig. 3.1 shows a schematic diagram of the SPVG inter-connected to an upstream grid system. Thevenin equivalent model is used to represent the grid, as the interconnected system external to the SPVG is complex. Accordingly, in Fig. 3.1(a), E_S is the open-circuit voltage of the equivalent grid source. Z_S is the source impedance. Hence, in the context of the present investigation on tightly-coupled networks, Z_S (in p.u.) tends to be small in comparison to the load impedance. $\bar{V}_L$, $\bar{V}_S$, $\bar{V}_i$ and $\bar{I}_i$ denote the load, PCC and the SPVG injected voltages and the injected/load

(a)

(b)

Fig. 3.1 (a) Schematic diagram of the series-connected photovoltaic generator interconnected to a grid system (b) SPVG phasor diagrams.

current phasors respectively. The SPVG and the upstream source operate to meet the constant load demand $\bar{S}_L = P_L + jQ_L$. The relevant phasor diagram relating the voltages and current is also shown in Fig. 3.1(b).

For distributed network applications, the SPVG is likely to be a single-phase device. Hence this investigation shall consider only one phase of the three-phase system. If one assumes a large number of the SPVGs are evenly distributed among the three phases in the distribution system, then the following analysis shall be for the single-phase equivalent of the balanced 3-phase system.

3.2.1. General Description of the SPVG

When the grid system is under normal state, the PV modules capture photovoltaic power (P_{PV}) from the sun. The SPVG output power P_i is then injected into the external grid-load system. Fig. 3.1 shows the conversion from P_{PV} to P_i is through a DC/DC boost convertor and a DC-AC inverter. At any given time, P_{PV} depends on the solar insolation level and the operating temperature of the PV modules [203]. At each insolation level, there is a unique operating state of the modules by which maximum power can be extracted. The DC-DC converter is used to guarantee maximum power point tracking (MPPT) while the inverter effects power flows control to the grid through regulating the injected complex power $P_i + jQ_i$. If losses in the converters are negligible, the SPVG output power $P_i = P_{PV}$. In order to achieve maximum utilization ratio, the voltage ripples at the output of the PV modules must be limited. The capacitor (C_{PV}) is therefore added to reduce the ripples. Furthermore, a power decoupling capacitor (C_{DC}) is required between the two conversion stages of the SPVG. C_{DC} provides an energy buffer medium in the DC-link of the inverter [149]. This capacitor can be utilized as an energy storage device during grid voltage disturbance and this function shall be further examined later. The SPVG also includes an injecting transformer to boost the voltage of the inverter and to provide galvanic isolation.

3.2.2. SPVG Design Objectives

While the SPVG can be readily controlled through the DC/DC converter to maximize energy harness from the sun, however, P_i will vary with changes in the

solar insolation level. Hence in terms of voltage quality enhancement, the challenge is to ensure the load voltage magnitude (V_L) is maintained constant, although the voltage phase angle θ is permitted to vary. One function of the inverter control system is to regulate V_L , through adjusting the SPVG injected power. Yet another possible scenario considered earlier is the occurrence of grid voltage disturbances. Such voltage disturbances can be represented as changes in E_s . Again the control system of the SPVG is to adjust the injected P_i and Q_i so as to maintain V_L constant at the pre-disturbance level.

With the above design objectives in mind for the SPVG, a phasor analysis can be carried out so as to gain a better understanding of the design problem.

3.3. Analysis and Control of SPVG Operations: Without Energy Storage

As explained earlier, as the insolation level varies or when an upstream disturbance occurs, the objective is to maintain V_L by adjusting the SPVG output power.

3.3.1. Feasible Operating State of SPVG

By applying KVL, power balance and phasor analysis to Fig. 3.1, the following steady-state equations can be obtained:

$$\bar{V}_L = \bar{V}_i + \bar{E}_s - \bar{Z}_s \bar{I}_i \quad (3.1)$$

Complex power of load and SPVG are given as respectively,

$$\bar{V}_L \bar{I}_L^* = P_L + jQ_L \quad (3.2)$$

$$\bar{V}_i \bar{I}_i^* = P_i + jQ_i \quad (3.3)$$

Complex load is

$$\bar{S}_L = P_L + jQ_L \quad (3.4)$$

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Whence load current can be calculated from (3.5) and similarly, SPVG current can be obtained from (3.6)

$$\bar{I}_L = \frac{P_L - jQ_L}{\bar{V}_L^*} \quad (3.5)$$

$$\bar{I}_i = \frac{P_i - jQ_i}{\bar{V}_i^*} \quad (3.6)$$

SPVG is in series connection with the upstream grid and load. Therefore the load and SPVG currents are equal. Thus $\bar{I}_i = \bar{I}_L$, i.e.

$$\frac{P_L - jQ_L}{\bar{V}_L^*} = \frac{P_i - jQ_i}{\bar{V}_i^*} \quad (3.7)$$

Taking conjugate operation on both sides of (3.7), one obtains

$$\bar{V}_L = \frac{P_L + jQ_L}{P_i + jQ_i} \bar{V}_i \quad (3.8)$$

$$\bar{V}_i = \frac{P_i + jQ_i}{P_L + jQ_L} \bar{V}_L \quad (3.9)$$

Using (3.1) and (3.9), therefore

$$\bar{V}_L = \frac{P_i + jQ_i}{P_L + jQ_L} \bar{V}_L + (\bar{E}_S - \bar{Z}_S \bar{I}_i) \quad (3.10)$$

$$\bar{V}_L \left(\frac{(P_L - P_i) + j(Q_L - Q_i)}{P_L + jQ_L} \right) = \bar{E}_S - \bar{Z}_S \bar{I}_i \quad (3.11)$$

Substituting $\bar{I}_i$ of (3.6) into (3.11), therefore

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$$\bar{V}_L \left(\frac{(P_L - P_i) + j(Q_L - Q_i)}{P_L + jQ_L} \right) = \bar{E}_s - \bar{Z}_s \frac{P_L - jQ_L}{\bar{V}_L^*} \quad (3.12)$$

Multiply both sides of (3.12) with $\bar{V}_L^*$, one can write

$$V_L^2 \left(\frac{(P_L - P_i) + j(Q_L - Q_i)}{P_L + jQ_L} \right) = \bar{E}_s \bar{V}_L^* - \bar{Z}_s (P_L - jQ_L) \quad (3.13)$$

Also multiply both sides of (3.13) with $P_L + jQ_L$

$$V_L^2 [(P_L - P_i) + j(Q_L - Q_i)] = \bar{E}_s \bar{V}_L^* (P_L + jQ_L) - \bar{Z}_s (P_L^2 + Q_L^2) \quad (3.14)$$

$$V_L^2 [(P_L - P_i) + j(Q_L - Q_i)] = \bar{E}_s \bar{V}_L^* (P_L + jQ_L) - \bar{Z}_s S_L^2 \quad (3.15)$$

Referring to Fig. 3.1(b), $\bar{V}_L = V_L \cos \theta + j V_L \sin \theta$. Substitute this last equation into (3.15), and after some mathematical manipulation, one obtains

$$V_L^2 [(P_L - P_i) + j(Q_L - Q_i)] = \bar{E}_s (V_L \cos \theta - j V_L \sin \theta) (P_L + jQ_L) - (R_s + jX_s) S_L^2 \quad (3.16)$$

$$V_L^2 [(P_L - P_i) + j(Q_L - Q_i)] - \bar{E}_s (V_L \cos \theta - j V_L \sin \theta) (P_L + jQ_L) + (R_s + jX_s) S_L^2 = 0 \quad (3.17)$$

$$V_L^2 (P_L - P_i) + j V_L^2 (Q_L - Q_i) + (-E_s P_L V_L \cos \theta - E_s Q_L V_L \sin \theta) + j(-E_s Q_L V_L \cos \theta + E_s P_L V_L \sin \theta) + (R_s S_L^2 + jX_s S_L^2) = 0 \quad (3.18)$$

By separation of real and imaginary parts of (3.18), the following equations can be obtained:

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$$\left. \begin{aligned} V_L^2(P_L - P_i) + (-E_S P_L V_L \cos \theta - E_S Q_L V_L \sin \theta) + R_S S_L^2 &= 0 \\ V_L^2(Q_L - Q_i) + (-E_S Q_L V_L \cos \theta + E_S P_L V_L \sin \theta) + X_S S_L^2 &= 0 \end{aligned} \right\} \quad (3.19)$$

For the design problem in hand, (3.19) can be interpreted in the following way. The upstream source and load are characterized by the parameters E_S , P_L , Q_L , S_L , R_S and X_S . For a given upstream and load system, these parameters are known. Also at a given insolation level, i.e. given P_{PV} , and by ignoring firstly the stored energy in C_{DC} , $P_i = P_{PV}$. As the load voltage is to be maintained at a given constant value V_L , the remaining unknowns θ and Q_i can be determined by solving (3.19), yielding

$$\theta = -\arccos\left(\frac{V_L(P_L - P_i)}{S_L E_S} + \frac{R_S S_L}{V_L E_S}\right) + \varphi \quad (3.20)$$

$$Q_i = Q_L - E_S \frac{S_L}{V_L} \sin(\varphi - \theta) + \frac{X_S S_L^2}{V_L^2} \quad (3.21)$$

Furthermore, it can be readily shown that P_i must satisfy the following inequality conditions in order to guarantee that real solutions exist for (3.20) and (3.21):

$$P_L - E_S I_i + R_S I_i^2 \leq P_i \leq P_L + E_S I_i + R_S I_i^2 \quad (3.22)$$

Thus (3.22) shows that for a given upstream source and load condition, the load voltage can be maintained at the level V_L , provided P_i is above a minimum level $P_{i,min}$ where

$$P_{i,min} = P_L - E_S I_i + R_S I_i^2 \quad (3.23)$$

As can be seen in (3.20) - (3.22), Z_S should be known in order to solve for the

unknowns θ , P_i and Q_i . One simple method to estimate Z_S is based on the short circuit ratio (SCR) and the ratio of X_S/R_S . Other more sophisticated techniques can also be used to estimate Z_S [204, 205]. Since the determination of Z_S is not the focus in this research, Z_S has been estimated based on SCR and X_S/R_S ratio in the subsequent calculations.

The outcome of the analysis can be illustrated most effectively by referring to Fig. 3.2. It shows a family of curves governing the SPVG injected power $P_i + jQ_i$ obtained by solving (3.19) – (3.21), in order to maintain V_L at a specified value of $V_{L,n}$. Each curve corresponds to a given value of E_S . There is, however, a practical limit placed on the output power loading of the SPVG inverter. The output power must be such that

Fig. 3.2 Family of P_i - Q_i curves of the SPVG required to maintain load voltage at $V_{L,n}$ at various E_S : SPVG of apparent power rating $S_{r,k}$.

$$\sqrt{P_i^2 + Q_i^2} \leq S_{r,k} \quad (3.24)$$

In (3.24), $S_{r,k}$ is the apparent power rating of the inverter, where k is an index to indicate power rating of a particular value. The constraint (3.24) is necessary to prevent overloading the inverter when the SPVG attempts to achieve the voltage control. Thus this practical constraint on the injected power must be included in the figure. An example of this power constraint is represented by the semi-circle $S_{r,k}$ in Fig. 3.2.

Even if a solution set of (P_i, Q_i) is within the semi-circle, it can also be shown that not all such sets of (P_i, Q_i) would lead to real solution for θ and Q_i . Indeed, there is an upper limit placed on the solution sets of (P_i, Q_i) below which the real solutions for θ and Q_i are guaranteed. This additional constraint on (P_i, Q_i) is shown as the linear boundary CF in Fig. 3.2. It should be noted that the upper boundary also depends on the power rating of SPVG. Therefore for relatively smaller inverter power rating than $S_{r,k}$, the upper boundary could be outside the semicircle describing the inverter apparent power limit.

In summary, therefore, by considering the finite apparent power rating of the SPVG inverter, the feasible steady state value of the injected power $P_i + jQ_i$ is within the boundary ABFCEA in Fig. 3.2 for the SPVG power rating of $S_{r,k}$.

With reference to Fig. 3.2, suppose the upstream system is under normal state, i.e. $\bar{E}_S = E_{S,0} \angle 0$. Consider the scenario when the solar insolation level varies which in turn causes P_{PV} (and therefore P_i) to vary. Once this occurs, the feasible operating range of the SPVG output power P_i is when P_i is between 0 to $P_{i,A}$. This is because if P_i exceeds $P_{i,A}$, the SPVG shall not be able to maintain the load voltage at $V_{L,n}$ without overloading its inverter. Hence, the feasible operating state of the SPVG under this scenario corresponds to that part of the curve DA when $E_S = E_{S,0}$.

3.3.2. Impacts of Grid System Voltage Sags/Swells on SPVG Operations

Under this upstream voltage disturbance scenario, one would expect the solar insolation variations to be small over the relatively short duration of a typical sag/swell. P_{PV} (and hence SPVG injected power P_i) is assumed constant during the

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voltage sag/swell. In this study, a sag/swell event is represented by a sudden decrease/increase in the upstream source voltage and the quasi-steady state remaining (standing) value of E_S is denoted as $E_{S,l}$ or $E_{SW,l}$ for the respective sag or swell event l .

Consider firstly sag event l . The intended role of the SPVG is to maintain the load voltage constant at $V_{L,n}$ during the sag. The transient process when mitigating the sag is complex and involves the dynamic interactions of the grid system with the SPVG. Depending on the response characteristics of the designed SPVG, typically a quasi-steady state of the process would have been reached about a cycle or so after the incipient of the sag event. In this manner, the phasor analysis can still apply in analyzing the quasi-steady state.

Suppose the SPVG power rating is $S_{r,k}$ and the pre-sag $E_S = E_{S,0}$. Thus the SPVG pre-sag output power operating state corresponds to the point H in Fig 3.2. During the sag, $E_S = E_{S,l}$. Thus the quasi-steady state operating state of the SPVG during the sag must shift from H to G. This is because P_i has been assumed to be constant during the sag incident and hence, the output reactive power of the SPVG has to change from $Q_{i,H}$ to $Q_{i,G}$ in order to keep the load voltage at $V_{L,n}$. On the other hand, the minimum injected power $P_{i,min,l}$ required to maintain the load voltage at $V_{L,n}$ can be calculated using (3.23) while considering the power rating limits (3.24). In this instance and within the feasible operating boundary ABFCEA, $P_{i,min,l}$ would correspond to that under the operating state B₂ for $E_S = E_{S,l}$. Since $P_i \geq P_{i,min,l}$, therefore, the load voltage can be restored to $V_{L,n}$ because there is sufficient injected power from the SPVG. On the other hand, if a deeper voltage sag were to occur, e.g. $E_S = E_{S,n}$, the corresponding minimum injected power required to maintain the load voltage is $P_{i,min,n}$, as shown in Fig. 3.2. Since the available solar power P_i is less than $P_{i,min,n}$, load voltage restoration will not be successful. This latter example clearly illustrates the need of an ESS. The ESS can provide the balance of the injected power $P_{i,min,n} - P_i$ required to ensure successful voltage restoration. The incorporation of an ESS shall be considered in detail in Section 3.4.

In Fig 3.2, it shows that the deepest voltage sag that can be mitigated by the SPVG corresponds to the event $E_{S,q}$. This is because when $E_S = E_{S,q}$, the corresponding P_i - Q_i

curve is tangential to the semicircle $S_{r,k}$. The SPVG would not be able to mitigate voltage sag deeper than $E_{S,q}$ without overloading the inverter.

The above is based on the concept that the P_i - Q_i boundary ABFCDA prescribes the feasible voltage restoration capability area of the SPVG to mitigate an upstream sag disturbance. It means that any sag event which results in the SPVG operating within the shaded area ABFCDA in Fig. 3.2 can be mitigated by the SPVG as the SPVG output power loading shall be within the inverter rating of $S_{r,k}$. Provision of an ESS may be called for. However, load ride-through for the voltage sag $E_{S,z}$ cannot be achieved even with the ESS because the corresponding P_i - Q_i curve is completely outside the feasible area. Fig. 3.2 also shows that for the mitigation of shallow sags, the minimum injected active power required might be zero. An example is the sag case when $E_S = E_{S,a}$.

The same reasoning can be used in analyzing the mitigation of an upstream voltage swell. As can be seen in Fig. 3.2, the main difference in the feasible operating state of the SPVG under sag and swell condition is that very often, $P_{i,min} = 0$ for the mitigation of swells. In the case of high solar insolation (e.g. operating state A), the ability of the SPVG to mitigate voltage swell decreases because of the $S_{r,k}$ constraint. It therefore indicates again the need to an ESS: i.e., during voltage swell, the excess power is to be diverted to the ESS.

Based on the above, the voltage sag/swell mitigation capability of the SPVG is constrained within the shaded feasible operating area ABFCEA for the SPVG of power rating $S_{r,k}$. When a voltage sag/swell occurs, the SPVG has to adjust its output power to a new operating state which is governed by the P_i - Q_i curve for the given $E_{S,l}$ or $E_{SW,l}$.

3.4. Roles of Energy Storage: Determination of Capacitor capacitance

The main source of energy supply in the SPVG is the PV-module. From previous section, however, it is shown the capability of the SPVG to mitigate voltage sag/swell shall be constrained, unless an ESS such as the capacitor C_{DC} is available in the SPVG to act as an energy buffer. In this section, the roles of the capacitor ESS

in the operation of the SPVG are explained and a method to determine the required capacitance of C_{DC} shall be described.

3.4.1. Roles of C_{DC} During Voltage Sags/Swells

The analysis in Sections 3.3 shows that without the ESS, the load ride-through capability afforded by the SPVG generally decreases with the apparent power capacity S_r of the SPVG. It is reasonable to assume the inverter apparent power rating S_r shall be at least equal to the active power capacity of the PV modules, as the SPVG is intended to maximize the export of P_{PV} . Nevertheless, the viability of the SPVG shall be greatly improved if S_r can be reduced to the minimum while the SPVG's ability to maintain load voltage is maximized. This motivates the following analysis.

Section 3.3 has shown that when the solar insolation level is low or at nighttime, the SPVG can only mitigate shallow voltage sags unless an additional source of active power, in the form of an ESS, is available. In this study, C_{DC} is treated as the medium of energy storage. With C_{DC} so incorporated in the SPVG and with reference to Fig. 3.2, when the upstream source voltage sags to $E_{S,l}$, if P_i prior to the sag is such that $P_i < P_{i,min,l}$, then C_{DC} shall discharge at the very least the balance $P_{i,min,l} - P_i$ so that load low-voltage ride-through is achieved. In the event of a voltage swell, C_{DC} is to absorb the excess energy from the grid and may even allow the reversal of the power flow, i.e. $P_i \leq 0$. In this way, a wider range of voltage swell may be mitigated by the SPVG. The extent by which the mitigation can be successful depends on the energy storage capacity of C_{DC} .

3.4.2. A Deterministic Approach to Evaluate the Capacity of C_{DC}

Denote the rated voltage of C_{DC} as $V_{DC,n}$. In adopting the design of the SPVG shown on Fig. 3.1, suppose the voltage across C_{DC} can be allowed to vary between $V_{DC,min}$ and $V_{DC,n}$. $V_{DC,min}$ is the lower limit placed on V_{DC} in order to prevent the over-modulation of the PWM generator in the inverter. Consider the voltage sag event l which occurs during nighttime so that $P_{PV} = 0$. Under this most strenuous condition, C_{DC} shall then have to provide all the active power for the load ride-through plus any

power losses in the inverter circuit. Using energy balance principle, therefore the minimum capacitance of C_{DC} needed to ride through the event l is

$$C_{DC,l} = \frac{2 \cdot (P_{i,min,l} + P_{loss}) \cdot \Delta T_{max,l}}{(V_{DC,n})^2 - (V_{DC,min})^2} \quad (3.25)$$

In (3.25), $\Delta T_{max,l}$ denotes the maximum duration of the event l when the grid voltage drops to $E_{s,l}$ whereas $P_{i,min,l}$ is the minimum active power required to achieve the ride-through. P_{loss} is the total power loss in the inverter. Equation (3.25) shows that the three main factors which determine the minimum capacitance of C_{DC} are the maximum duration $\Delta T_{max,l}$ of $E_{s,l}$, the minimum active power ($P_{i,min,l}$) required to ride through $E_{s,l}$ and power loss (P_{loss}). With (3.25), C_{DC} may be determined to meet specific voltage sag ride-through standards such as that described in [206, 207].

A possible alternative to the above deterministic approach is to utilize the results of power quality survey such as that shown in [41] and adopt a statistical approach to solve the design problem. By treating the input solar power and sag events as random events, a judicious decision can be made with regard to the determination of the required capacity of the capacitor ESS and inverter rating, through balancing the benefit of improved sag/swell mitigation against the cost of the capacitor and inverter. The analysis and design procedure of this approach will be addressed later in Chapters 5 and 6.

3.5. SPVG Control Scheme

The above analysis provides the basis for the design of a control scheme for the SPVG. Components of the scheme are described in the following.

3.5.1. Boost Converter Control

Power flows between the PV panels and the grid are controlled by the DC/DC boost converter shown in Fig. 3.1. The converter adjusts the solar panel output voltage at regular interval so as to maximize P_{PV} through the use of maximum power point tracking (MPPT) technique. Performance of the classical perturb-and-observe (P&O)

MPPT technique is acceptable even under low solar insolation level condition, although its response time depends on the irradiation level [208]. The other popular so-called incremental conductance (IC) MPPT technique is faster than the P&O technique but its performance is somewhat lower than that based on the latter algorithm. Efficiency of the IC and P&O techniques is observed to be comparable when they are properly designed and under the same atmospheric condition [209, 210]. Based on these observations, the classical P&O MPPT method described in [209] has been adopted in the converter control scheme in the present investigation.

Fig. 3.3 shows the flowchart of the general algorithm of P&O MPPT method. In this method, after a perturbation on voltage in a particular direction, the calculated power ($P_{PV}[n]$) is compared to the power in the last step ($P_{PV}[n-1]$). If $P_{PV}[n] > P_{PV}[n-1]$, then the perturbation is in the correct direction so the direction of the next perturbation, Dir , is the same as before. Otherwise, Dir must be reversed.

Fig. 3.3 Flowchart of Perturb and Observed (P&O) MPPT.

3.5.2. Inverter Control

The control scheme for the inverter is shown in Fig. 3.4. It consists of a load voltage control loop. The closed-loop is to track the reference signal of the load voltage. In this project, the Phase Locked Loop (PLL) and Discrete Fourier Transform (DFT) methods have been used. The magnitude and phase angle of $v_S(t)$ are derived using the DFT and the second order generalized integrator-based PLL techniques described in [35] has also been adopted. These parameters will be used to determine $v_{L-ref}(t)$. The method to calculate v_{L-ref} will be explained in Section 3.5.4. In this way, it allows the load voltage reference signal $v_{L-ref}(t)$ shown in Fig. 3.4 to be determined. Due to the delay in the closed-loop system, a feedforward control has been added to track changes in $v_S(t)$ so as to enhance the dynamic performance of the system. This is similar to the approach described in [78]. The feedforward signal is formed from the difference between $v_S(t)$ and v_{L-ref} . Also, the closed-loop control scheme of series connected voltage source inverter has been shown to be effective in attenuating harmonic distortions [116]. Thus in the present work, the feedforward signal is also used to reduce the harmonic distortion level in $v_L(t)$ through adjusting the switching pattern of the PWM generator. Harmonic mitigation capability of the SPVG shall be validated by simulation in Section 3.6.2 and by the experimental tests to be described in Chapter 4.

In view of the above considerations, the SPVG inverter control system should

Fig. 3.4 Control block diagram of SPVG inverter.

provide an AC waveform with low harmonic distortion and appropriate dynamic response characteristics against supply and load disturbances. Thus the closed-loop controller is used to achieve higher stability margin, smaller steady state error and adequate damping at the output voltage. It should be noted that in general, open-loop control scheme based on the comparison between the reference voltage and source voltage cannot compensate voltage drop across the transformer series impedance and the filter impedances. Thus the close-loop control scheme is preferred over open-loop control scheme.

Control techniques used in [14, 182] for series connected PV inverter are spatial repetitive and adaptive proportional resonant controllers respectively. The techniques require much more intense computation compared to the proposed simple PI controller with feedforward control considered in this chapter.

In the following sections, the dynamic characteristics of the SPVG inverter are studied. According to the analysis presented in Sections 3.2 and 3.3, SPVG regulates the load voltage by adjusting its output injected active and reactive powers. Assume the load has an inductance L_L and resistance R_L , while the output filter has an inductance of L_f , a resistance of R_f and a capacitance of C_f . As the inverter includes power semiconductor switches, the SPVG is a nonlinear device. However the SPVG inverter behavior can be described using the state-space averaging technique and its dynamic characteristic is expressed by differential equations. During this investigation, a linear constant impedance load is assumed. This assumption is reasonable as the sag/swell voltage duration is much shorter than the time it would normally take for the load variations to be deemed appreciable.

3.5.2.1. SPVG under Open Loop Condition

With reference to Fig. 3.1, the following equations govern the dynamical behavior of the SPVG:

$$v_i = n(i_{Cf}R_f + v_c) - n^2 \left(i_L R_t + L_t \frac{di_L}{dt} \right) \quad (3.26)$$

$$i_{inv} = i_{Cf} + i_L \quad (3.27)$$

$$i_{Cf} = C_f \frac{dv_c}{dt} \quad (3.28)$$

$$v_i = R_L i_L + L_L \frac{di_L}{dt} - v_s \quad (3.29)$$

$$v_{inv} = L_f \frac{di_{inv}}{dt} + v_f \quad (3.30)$$

where v_c denotes the voltage across C_f and i_{inv} is inverter output current shown in Fig. 3.1(a). n represents the transformer turns-ratio. From these equations, Fig. 3.5 shows the block diagram of the SPVG under open-loop condition.

With reference to Fig. 3.5, the load voltage can be described as

Fig. 3.5 Block diagram representation of the SPVG under open-loop condition

$$v_L = G_{vlo} v_{L-ref} + G_{vso} v_s \quad (3.31)$$

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where G_{vlo} is the open-loop transfer function from v_{L-ref} to v_L while G_{vso} is that from v_s to v_L . Mathematically,

$$G_{vlo}(s) = \left. \frac{v_L(s)}{v_{L-ref}(s)} \right|_{v_s=0} \quad (3.32)$$

$$G_{vso}(s) = \left. \frac{v_L(s)}{v_s(s)} \right|_{v_{L-ref}=0} \quad (3.33)$$

The Mason's method [211] can be adopted to derive the open-loop transfer function of the SPVG system. Fig. 3.6 illustrates the signal flow graph for $G_{vlo}(s)$ where $G_1(s)$ - $G_4(s)$ are given by.

$$G_1(s) = \frac{1}{L_f s} \quad (3.34)$$

$$G_2(s) = \frac{1}{C_f s} + R_f \quad (3.35)$$

$$G_3(s) = \frac{n}{L_L s + R_L} \quad (3.36)$$

$$G_4(s) = \frac{n(L_t s + R_t)}{L_L s + R_L} \quad (3.37)$$

Fig. 3.6 Signal flow graph for G_{vlo}

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$G_{vlo}(s)$ is then obtained from the signal flow graph to yield

$$G_{vlo}(s) = \frac{v_L}{v_{L-ref}} = \frac{nK_{inv}G_1(s)G_2(s)}{1 + G_1(s)G_2(s) + nG_2(s)G_3(s) + nG_4(s) + nG_1(s)G_2(s)G_4(s)} \quad (3.38)$$

By substituting $G_1(s)$ - $G_4(s)$ into (3.38),

$$G_{vlo}(s) = \frac{nK_{inv} \left(\frac{1}{L_f s} \right) \cdot \left(\frac{1}{C_f s} + R_f \right)}{1 + \left(\frac{1}{L_f s} \right) \cdot \left(\frac{1}{C_f s} + R_f \right) + n \left(\frac{n}{L_L s + R_L} \right) \cdot \left(\frac{1}{C_f s} + R_f \right) + n^2 \left(\frac{L_t s + R_t}{L_L s + R_L} \right) + n^2 \left(\frac{1}{L_f s} \right) \cdot \left(\frac{1}{C_f s} + R_f \right) \left(\frac{L_t s + R_t}{L_L s + R_L} \right)} \quad (3.39)$$

$$G_{vlo}(s) = \frac{nK_{inv}(L_L s + R_L)(1 + R_f C_f s)}{a_{3o}s^3 + a_{2o}s^2 + a_{1o}s + a_{0o}} \quad (3.40)$$

where,

$$a_{0o} = n^2 R_t + R_L \quad (3.41)$$

$$a_{1o} = L_L + n^2 L_f + n^2 L_t + R_f C_f (R_L + n^2 R_t) \quad (3.42)$$

$$a_{2o} = n^2 C_f (L_f R_f + L_t R_f + R_t L_f) + (R_f L_L + R_L L_f) C_f \quad (3.43)$$

$$a_{3o} = (L_L + n^2 L_t) L_f C_f \quad (3.44)$$

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Next, Fig. 3.7 illustrates the signal flow graph for $G_{vso}(s)$. Again, $G_{vso}(s)$ is determined using signal flow graph of Fig. 3.7 to give

Fig. 3.7 Signal flow graph for G_{vso}

$$G_{vso}(s) = \frac{v_L}{v_s} = \frac{1 + G_1(s)G_2(s) - nK_{inv}G_1(s)G_2(s)}{1 + G_1(s)G_2(s) + nG_2(s)G_3(s) + nG_4(s) + nG_1(s)G_2(s)G_4(s)} \quad (3.45)$$

$$G_{vso}(s) = \frac{(L_f s + R_f)(L_L s + R_L)C_f s + (L_L s + R_L)(1 + R_f C_f s)(1 - nK_{inv})}{(L_f s)(L_L s + R_L)(C_f s) + (L_L s + R_L)(1 + R_f C_f s) + n^2(L_f s)(1 + R_f C_f s) + n^2(L_t s + R_t)(L_f s)C_f s + n^2(L_t s + R_t)(1 + R_f C_f s)} \quad (3.46)$$

$$G_{vso}(s) = \frac{L_L L_f C_f s^3 + (R_L L_f + L_L R_f (1 - nK_{inv}))C_f s^2 + ((1 - nK_{inv})(R_f R_L C_f + L_L))s + (1 - nK_{inv})R_L}{a_{3o}s^3 + a_{2o}s^2 + a_{1o}s + a_{0o}} \quad (3.47)$$

Equation (4.48) expresses the characteristic equation of the open loop system as

$$CEO = a_{3o}s^3 + a_{2o}s^2 + a_{1o}s + a_{0o} = 0 \quad (3.48)$$

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This equation has one real root and two complex conjugate roots. It can be shown that the real root is approximately located at $-(R_L+n^2R_t)/(L_L+n^2L_t)$. Hence, the characteristic equation can be rewritten as follows:

$$a_{3o}s^3 + a_{2o}s^2 + a_{1o}s + a_{0o} \approx q_{1o} \times \left\{ (L_L + n^2L_t)s + (R_L + n^2R_t) \right\} \times (s^2 + q_{2o}s + q_{3o}) \quad (3.49)$$

By equating the coefficients on both sides of (3.49), one obtains

$$q_{1o} = \frac{a_{3o}}{(L_L + n^2L_t)} = L_f C_f \quad (3.50)$$

$$q_{2o} = \frac{a_{2o} - (R_L + n^2R_t)q_{1o}}{(L_L + n^2L_t)q_{1o}} = \frac{R_f C_f L_L + n^2 R_f C_f L_f + C_f L_t n^2 R_f}{C_f L_f (L_L + n^2L_t)} \approx \frac{R_f}{L_f} \quad (3.51)$$

$$q_{3o} = \frac{a_{0o}}{(R_L + n^2R_t)q_{1o}} = \frac{R_L + n^2R_t}{(R_L + n^2R_t)L_f C_f} = \frac{1}{L_f C_f} \quad (3.52)$$

The stability of the open loop SPVG can be assessed using Routh-Hurwitz criteria. For the system to be stable, the characteristic equation (3.49) dictates the term $a_{1o}a_{2o} - a_{3o}a_{0o}$ must be greater than zero as $a_{2o} > 0$. It can be readily shown that this condition can be satisfied for all possible values of C_f , L_f , R_f , L_t , R_t , L_L , R_L and n . Therefore in the open-loop control scheme, the system is inherently stable. This fact can be re-examined by observing the roots of (3.49). All of the roots are in the left side of the complex plane. Unfortunately, the Routh-Hurwitz criteria cannot determine the degree of stability. Interested readers may wish to refer to [212] governing the general theory of Routh-Hurwitz criteria.

For the system under examination, the real part of the two dominant poles is equal to $-R_f/2L_f$. The value of the filter damping resistor R_f must be appropriately selected to obtain suitable damping. The transient response of the open loop system is very much like a second-order system with a damping constant of ξ_0 and natural

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damping frequency of ω_{n0} . The natural damping frequency of the system is approximately equal to the filter resonance frequency and the damping constant is dependent of the filter damping resistance. Thus,

$$\omega_{n0} \approx \sqrt{\frac{1}{L_f C_f}} \quad (3.53)$$

$$\xi_0 = \frac{R_f}{2L_f \omega_{n0}} \quad (3.54)$$

As indicated by (3.54), filter resistance must be increased if it is desirable to increase damping. Even though selecting a large R_f can improve damping, it is not a good practice as that would increase losses in the system and degrade the filtering capability.

The steady state error of the open loop system for a sinusoidal input can be shown to be

$$ESSO = \left[1 - \frac{K_{inv} \sqrt{(1 + R_f^2 C_f^2 \omega_0^2)(R_L^2 + L_L^2 \omega_0^2)}}{\sqrt{(a_{0o} - \omega_0^2 a_{2o})^2 + \omega_0^2 (a_{1o} - \omega_0^2 a_{3o})^2}} \right] \times 100 \quad (3.55)$$

Table A.1 in Appendix A provides the parameters of the SPVG shown in Fig 3.1. These parameters are used for the dynamic simulation of the SPVG in Chapter 3 and the experimental SPVG setup in Chapter 4. ESSO is about 5% for the SPVG system given in Table A.1.

The corresponding Bode plots of the transfer functions $G_{vlo}(s)$ and $G_{vso}(s)$ are shown in Fig. 3.8 and 3.9 respectively.

Fig. 3.8 shows that the load voltage tracks the reference voltage but with a steady state error. Fig 3.9 illustrates the Bode plot of $G_{vso}(s)$. Low frequency disturbances in the supply voltage are attenuated effectively and will not appear in the load voltage. However, supply voltage disturbances at frequency close to the filter resonance

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frequency can appear in the load voltage. As it can be seen in Fig. 3.9, the maximum order of harmonic which can be eliminated by the open-loop SPVG is about 5. Thus the open loop cannot be expected to provide suitable harmonic mitigation beyond the 5th order.

Fig. 3.8 Bode plot of transfer function G_{vlo}

Fig. 3.9 Bode plot of transfer function G_{vso}

The above analysis shows that the steady-state performance of the open-loop control SPVG system is less than desirable. Although integral controller can reduce the steady state error, it can degrade the SPVG transient response. Another option is to use the proportional-derivative controller. It can improve the transient response of the system but it is not suitable for noisy condition under which the SPVG could operate. Therefore only proportional controller is considered for the closed-loop controlled SPVG system in the next section.

3.5.2.2. *SPVG under closed-loop*

In this control scheme, the inverter utilizes a closed-loop to track the reference load voltage v_{L-ref} . This control loop is relatively simple to implement. There are alternative solutions for series connected voltage source inverters. In [213] for example, the filter capacitor current is used to form an internal current loop and it can provide adequate damping. Without it, poor damping leads to voltage oscillation at the load side. Although such current loop control improves stability margin and provides more degree of freedom in the design, it needs an additional current sensor. Therefore unlike [213], the inner current loop described there has been omitted and a passive damping method using a damping resistor R_f in series with C_f has been utilized. Fig 3.10 shows the closed-loop control block diagram for the SPVG inverter where it shows the load voltage v_L is compared with v_{L-ref} and the error is multiplied with the voltage gain K_v . The resulting quantity is added with feedforward voltage, the resulting value is fed to the SPWM generator of the inverter. Based on Fig. 3.10, the load voltage can be described as

$$v_L = G_{vlc} v_{L-ref} + G_{vsc} v_s \quad (3.56)$$

where $G_{vlc}(s)$ is the closed-loop transfer function from the v_{L-ref} to v_L while $G_{vsc}(s)$ is that from v_s to v_L . Mathematically,

$$G_{vlc}(s) = \left. \frac{v_L(s)}{v_{L-ref}(s)} \right|_{v_s=0} = \frac{b_{2c}s^2 + b_{1c}s + b_{0c}}{a_{3c}s^3 + a_{2c}s^2 + a_{1c}s + a_{0c}} \quad (3.57)$$

$$G_{vsc}(s) = \left. \frac{v_L(s)}{v_s(s)} \right|_{v_{L-ref}=0} = \frac{d_{3c}s^3 + d_{2c}s^2 + d_{1c}s + d_{0c}}{a_{3c}s^3 + a_{2c}s^2 + a_{1c}s + a_{0c}} \quad (3.58)$$

Fig. 3.10 Block diagram representation of the SPVG with closed-loop feedback controller

Again, using Mason's method, the relationship of the output voltage with respect to the reference input is obtained from the signal flow graph shown in Fig. 3.11. $G_1(s)$, $G_2(s)$, $G_3(s)$ and $G_4(s)$ are given by Equation (3.34), (3.35), (3.36) and (3.37) respectively.

Fig. 3.11 Signal flow graph for $G_{v/c}$

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$$G_{vlc}(s) = \frac{v_L(s)}{v_{L-ref}(s)} \Big|_{v_s=0} = \frac{nK_v K_{inv} G_1(s) G_2(s) + nK_{inv} G_1(s) G_2(s)}{1 + G_1(s) G_2(s) + nG_2(s) G_3(s) + nG_4(s) + nK_v K_{inv} G_1(s) G_2(s) + nG_1(s) G_2(s) G_4(s)} \quad (3.59)$$

$$G_{vlc}(s) = \frac{(nK_v K_{inv} + nk_{inv}) \left(\frac{1}{L_f s} \right) \left(\frac{1}{C_f s} + R_f \right)}{1 + \left(\frac{1}{L_f s} \right) \left(\frac{1}{C_f s} + R_f \right) + n \left(\frac{1}{C_f s} + R_f \right) \left(\frac{n}{L_t s + R_L} \right) + n \frac{n(L_t s + R_t)}{L_t s + R_L} + nK_v K_{inv} \left(\frac{1}{L_f s} \right) \left(\frac{1}{C_f s} + R_f \right) + n \left(\frac{1}{L_f s} \right) \left(\frac{1}{C_f s} + R_f \right) \left(\frac{n(L_t s + R_t)}{L_t s + R_L} \right)} \quad (3.60)$$

$$G_{vlc}(s) = \frac{(nK_v K_{inv} + nk_{inv})(1 + R_f C_f s)(L_t s + R_L)}{a_{3c} s^3 + a_{2c} s^2 + a_{1c} s + a_{0c}} \quad (3.61)$$

where,

$$a_{0c} = n^2 \times R_t + R_L (1 + nk_{inv} K_v) \quad (3.62)$$

$$a_{0c} = a_{0o} + nK_{inv} K_v R_L \quad (3.63)$$

$$a_{1c} = L_L + n^2 L_f + n^2 L_t + C_f R_f R_L + n^2 C_f R_f R_t + nL_L K_{inv} K_v + nC_f K_{inv} K_v R_f R_L \quad (3.64)$$

$$a_{1c} = a_{1o} + nK_{inv} K_v (L_L + R_f R_L C_f) \quad (3.65)$$

$$a_{2c} = L_L C_f R_f + C_f L_f R_L + n^2 C_f L_f R_f + n^2 C_f L_f R_t + n^2 C_f L_t R_f + nL_L C_f K_{inv} K_v R_f \quad (3.66)$$

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$$a_{2c} = a_{2o} + nL_L C_f K_{inv} K_v R_f \quad (3.67)$$

$$a_{3c} = a_{3o} = n^2 C_f L_f L_t + L_L C_f L_f \quad (3.68)$$

$$b_{0c} = nR_L K_{inv} (1 + K_v) \quad (3.69)$$

$$b_{1c} = n(L_L K_{inv} + L_L K_{inv} K_v + C_f K_{inv} R_f R_L + C_f K_{inv} K_v R_f R_L) \quad (3.70)$$

$$b_{2c} = n(L_L C_f K_{inv} R_f + L_L C_f K_{inv} K_v R_f) \quad (3.71)$$

The closed-loop transfer function from the $v_s(s)$ to $v_L(s)$ is obtained from the signal flow graph shown in Fig. 3.12.

Fig. 3.12 Signal flow graph for G_{vsc}

$$G_{vsc}(s) = \frac{v_L(s)}{v_s(s)} \bigg|_{v_L - ref = 0} = \frac{(1 + G_1(s)G_2(s)) - nK_{inv}G_1(s)G_2(s)}{1 + G_1(s)G_2(s) + nG_2(s)G_3(s) + nG_4(s) + nK_vK_{inv}G_1(s)G_2(s) + nG_1(s)G_2(s)G_4(s)} \quad (3.72)$$

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$$G_{vsc}(s) = \frac{d_{3c}s^3 + d_{2c}s^2 + d_{1c}s + d_{0c}}{a_{3c}s^3 + a_{2c}s^2 + a_{1c}s + a_{0c}} \quad (3.73)$$

$$d_{0c} = R_L(1 - nK_{inv}) \quad (3.74)$$

$$d_{1c} = L_L - nL_LK_{inv} + C_fR_fR_L - nC_fK_{inv}R_fR_L \quad (3.75)$$

$$d_{2c} = L_LC_fR_f + C_fL_fR_L - nL_LC_fK_{inv}R_f \quad (3.76)$$

$$d_{3c} = L_LC_fL_f \quad (3.77)$$

The characteristic equation of the closed-loop system (*CEC*) is given by

$$CEC = a_{3c}s^3 + a_{2c}s^2 + a_{1c}s + a_{0c} \quad (3.78)$$

Steady state error of closed-loop system *ESSC* for a sinusoidal input is given by

$$ESSC = \left[1 - \frac{nK_{inv}(K_v + 1)\sqrt{(1 + R_f^2C_f^2\omega_0^2)(R_L^2 + L_L^2\omega_0^2)}}{\sqrt{(a_{0c} - \omega_0^2a_{2c})^2 + \omega_0^2(a_{1c} - \omega_0^2a_{3c})^2}} \right] \quad (3.79)$$

Based on Routh-Hurwitz criteria, the term $(a_{1c}a_{2c} - a_{3c}a_{0c})/a_{2c}$ must be positive if the closed-loop system is to be stable. Since $a_{3c} > 0$ and $a_{2c} > 0$, therefore $a_{1c}a_{2c} - a_{3c}a_{0c}$ must be greater than zero. Since

$$\begin{aligned} a_{1c}a_{2c} - a_{0c}a_{3c} &= L_LC_fK_{inv}^2n^2R_f(L_L + C_fR_fR_L)K_v^2 + \\ &[a_{2o}K_{inv}n(L_L + C_fR_fR_L) - na_{3o}K_{inv}R_L + nL_La_{1o}C_fK_{inv}R_f]K_v + a_{1o}a_{2o} - a_{0o}a_{3o} \end{aligned} \quad (3.80)$$

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As shown in the open-loop system, $a_{1o}a_{2o}-a_{3o}a_{0o} > 0$ and K_v is a real number, in order to guarantee that $a_{1c}a_{2c}-a_{3c}a_{0c} > 0$, then it can easily be shown that K_v must satisfy the following inequality for stability to be guaranteed:

$$K_v > \frac{-(a_{2o}K_{inv}n(L_L + C_f R_f R_L) - na_{3o}K_{inv}R_L + nL_L a_{1o}C_f K_{inv}R_f)}{L_L C_f K_{inv}^2 n^2 R_f (L_L + C_f R_f R_L)} \quad (3.81)$$

Using the parameters of Table A.1, the Routh-Hurwitz criteria shows the system is stable when $K_v > -2.3$, although the degree of stability cannot be determined by the Routh-Hurwitz method.

Similar to analysis presented in Section 3.5.2.1, it can be seen that the real (non-dominant) root of the characteristic equation of the closed-loop system can be approximately located at $-\left(\frac{R_L + n^2 R_t}{L_L + n^2 L_t}\right)$. Factorization of the characteristic equation yields,

$$a_{3c}s^3 + a_{2c}s^2 + a_{1c}s + a_{0c} \approx q_{1c} \left\{ (L_L + n^2 L_t)s + (R_L + n^2 R_t) \right\} \cdot (s^2 + q_{2c}s + q_{3c}) \quad (3.82)$$

where,

$$q_{1c} = \frac{a_{3c}}{(L_L + n^2 L_t)} = L_f C_f \quad (3.83)$$

$$q_{2c} = \frac{a_{2c} - (R_L + n^2 R_t) \times q_{1c}}{(L_L + n^2 L_t) \times q_{1c}} \approx \frac{R_f}{L_f} (1 + nK_{inv}K_v) \quad (3.84)$$

$$q_{3c} = \frac{a_{0c}}{(R_L + n^2 R_t) \times q_{1c}} = \frac{R_L + n^2 R_t + nK_{inv}K_v R_L}{L_f C_f (R_L + n^2 R_t)} \quad (3.85)$$

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It can be easily shown that the real part of the two complex poles is $-\frac{R_f}{2L_f}(1+nK_{inv}K_v)$ and it depends on the values of the filter inductance, filter damping resistance as well as the inverter controller coefficient gain K_v . Thus the two complex poles are independent of load parameters. For a given K_{inv} , the value of K_v can be chosen such that the real part of the complex poles are far away from imaginary axis and the damping level can be increased with an increase of K_v . Therefore there is an additional degree of design flexibility compared to the open-loop SPVG system.

The natural frequency of the closed-loop SPVG system (ω_{nc}) and damping constant (ξ_{nc}) are given by:

$$\omega_{nc} = \sqrt{\frac{R_L + n^2 R_t + nK_{inv}K_v R_L}{L_f C_f (R_L + n^2 R_t)}} \approx \sqrt{\frac{1 + nK_{inv}K_v}{L_f C_f}} = \sqrt{(1 + nK_{inv}K_v)} \times \sqrt{\frac{1}{L_f C_f}} \quad (3.86)$$

$$\omega_{nc} = \omega_{n0} \sqrt{(1 + nK_{inv}K_v)} \quad (3.87)$$

$$\xi_{nc} = \frac{R_f}{2L_f \omega_{nc}} (1 + nK_{inv}K_v) \quad (3.88)$$

The natural damping frequency of the closed-loop system is approximately $\sqrt{(1 + nK_{inv}K_v)}$ times of the filter resonance frequency. Thus K_v can then be chosen to achieve the desired damping once the other parameters on the right hand side of (3.88) are known.

As an illustration, Fig. 3.13 shows the root loci of $G_{v/c}(s)$ with varied inverter voltage gain K_v using (3.82)-(3.85) for a given load of 0.8 power factor. This example is based on the SPVG system described under Table A.1. It can be seen that with the increase of K_v , the complex poles move away from the imaginary axis, thus resulting in a system with improved stability. Also from (3.88), one can determine that increasing K_v tends to increase the damping level and it is consistent with the

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location of dominant poles in Fig. 3.13. However, for lagging power factor load and control parameter presented in Table A.1, the system can achieve reasonable stability and damping level. The damping frequency of inverter control is about 14000 rad/s and ζ is about 0.21.

From the frequency response of $G_{v/c}(s)$ in Figure 3.14, it is clear that over the low frequency range, the output voltage tracks its reference precisely while high-

Fig. 3.13 Root loci of SPVG inverter closed-loop control system for different K_v

Fig. 3.14 Bode plot of transfer function $G_{v/c}$

frequency noise is attenuated. Moreover, the frequency response of $G_{vsc}(s)$ in Fig. 3.15 shows that low frequency disturbances of the supply are effectively rejected. These results are in agreement to the analysis presented in [116] for series connected voltage source inverters.

Fig. 3.15 Bode plot of transfer function G_{vsc}

3.5.3. DC-link Voltage Control

The DC-link interconnects the PV panels with the grid, and the DC-link voltage has to be regulated to allow the exchange of power between C_{DC} and the AC system. The control scheme for the DC-link voltage is shown in Fig. 3.16. It is shown that P_{PV} is used as an additional feedforward signal so that the effect of a change in P_{PV} can be rapidly used to adjust the control signal P_i^* , and thus compensates its impact on V_{DC} . An anti-windup mechanism has also been incorporated in the PI controller to discharge the integrator of the controller to avoid integrator wind up.

Since the DC-link voltage controller uses negative feedback, after some voltage sag incidents, due to the discharge of the capacitor during the voltage ride-through process, $V_{DC} < V_{DC-ref}$. Thus in order to return V_{DC} back to V_{DC-ref} , the DC-link controller reduces the injected power reference signal P_i^* so that $P_{PV} > P_i^*$. This surplus power from the PV used to

recharge the capacitor and increase the voltage in the DC-link. If the PV source is not available (e.g. nighttime) or very low, then P_i^* must be negative to absorb energy from the grid in order to maintain V_{DC} level. In cases of voltage swell, the DC-link voltage rises, i.e. $V_{DC} > V_{DC-ref}$. In order to adjust V_{DC} , the DC-link controller increases the output power of the SPVG to be higher than P_{PV} . The balance of the power between P_{PV} and P_i^* has to be extracted from the capacitor. Hence, the capacitor discharges, causing V_{DC} to reduce and restore it back to V_{DC-ref} .

Fig. 3.16 Block diagram for DC-link voltage controller

3.5.4. Overall Control System

The above control schemes are integrated into the overall control system shown in Fig. 3.17. In the figure, P_i^* is the output of the DC-link voltage controller and it is the amount of power that must be exchanged with the AC system in order to maintain V_{DC} at the pre-set value V_{DC-ref} . Under the normal upstream condition, $P_{i-ref} = P_i^*$. During a subsequent sag/swell incident, the control system is to determine $P_i + jQ_i$ required for maintaining $V_L = V_{L,n}$. Therefore the control strategy for restoring the load voltage, as explained in Section 3.3, shall be used. Thus P_{i-ref} shall be adjusted as follows:

- During the normal upstream state: $P_{i-ref} = P_i^*$.
- During upstream voltage sag: If $P_i^* \leq P_{i,min}$ then $P_{i-ref} = P_{i,min}$, otherwise $P_{i-ref} = P_i^*$.
- During upstream voltage swell: If $P_i^* > 0$ then $P_{i-ref} = 0$, otherwise $P_{i-ref} = P_i^*$.

Fig. 3.17 Overall control schematic diagram of SPVG.

The above rules are incorporated in the “ P_{i-ref} calculation” block in Fig. 3.17 to yield P_{i-ref} . Next, θ is determined by substituting $P_i = P_{i-ref}$ into (3.20). By adjusting θ , the active and reactive powers of the SPVG will change in such a manner as to keep the load voltage at $V_{L,n}$. With known θ and since it is assumed that $\bar{E}_S \approx \bar{V}_S$, the load voltage reference signal $v_{L-ref}(t)$ can be calculated as follows. $v_{L-ref}(t)$ can be expressed in the form $v_{L-ref}(t) = \sqrt{2} V_{L,n} \times \sin(\rho(t) + \theta)$ where $\rho(t)$ is the argument of the grid source voltage $v_s(t)$. $\rho(t)$ can be obtained using PLL applied to $v_s(t)$. Thus $v_{L-ref}(t)$ is obtained and it forms the input signal for the inverter control system shown in Fig 3.4. The output of the inverter control system is fed to the PWM generator to drive the power electronic switches.

3.6. Numerical Example

Numerical examples shall now be used to illustrate the above design approach. Load and Z_S are assumed known, as follows: load $\bar{S}_L = 345.6 + j259.2$ VA, i.e. $S_L = 432$ VA. Assume the SPVG is connected to a strong AC system and $\bar{Z}_S = 0.005 + j0.06$ p.u. (on 432 VA base) and the mains frequency is 50 Hz. These parameters were

selected so that they correspond to those seen in a prototype SPVG constructed in the author's laboratory and described in the next chapter.

Also, the data from the two-year power quality survey of electrical disturbances described in Table 8 of [41] has been adopted in this study. It is assumed the voltage quality performance in this study is similar to that shown in the survey.

3.6.1. Determination of C_{DC} Capacitance

Suppose the SPVG power rating ($S_{r,j}$) is 172.8 VA (i.e. 0.4 p.u.), nominal voltage of the DC-link ($V_{DC,n}$) is 200 V, minimum DC-link voltage ($V_{DC,min}$) is 60 V. Again the parametric values are consistent with those appearing in the prototype SPVG built in the author's laboratory.

Based on the assumed $\bar{S}_L$ and Z_S and by carrying out the analysis described in Section 3.3, it can be shown that voltage sags of between 0.6 - 0.9 p.u. can be mitigated by the SPVG. As has been explained in Section 2.6.2 where Table 2.3 has been extracted from [41] for the category of voltage sags within the range $0.6 < E_S \leq 0.7$ p.u., the number of events with duration longer than 0.5 s is shown to be negligible because only 0.3 events have duration more than 0.5. Hence on the basis of this observation, $\Delta T_{max,l}$ in (3.25) was assumed to be 0.5 s and the corresponding $P_{i,min,l}$ was found to be 0.31 p.u. (i.e. 133.92 W). Substituting these values into (3.25), one obtains the required minimum capacitance of 4.9 mF for C_{DC} . The same design procedure was repeated for other voltage sag categories. It was found that when $E_S = 0.7$ p.u. and $\Delta T_{max} = 1$ s, minimum C_{DC} required was 7.0 mF and it was the largest capacitance required among the sag states considered. Hence 7.0 mF was selected as the capacitance of C_{DC} .

Next, the probability of successful voltage sag mitigation can be obtained as follows. Refer to Table 2.3, the SPVG with $C_{DC} = 7$ mF is able to mitigate those voltage sags within the range $0.6 < E_S \leq 0.7$ and of duration less than 0.5 sec, those of $0.7 < E_S \leq 0.8$ with duration less than 1.0 sec and those of $0.8 < E_S \leq 0.9$ with duration less than 2 sec. Using (2.21) for each of the above mentioned sag severity results in the total probability of voltage sag that can be mitigated. Thus,

$prob(0.8 < E_S \leq 0.9, 0 < t_S \leq 2) + prob(0.7 < E_S \leq 0.8, 0 < t_S \leq 1.0) + prob(0.6 < E_S \leq 0.7, 0 < t_S \leq 0.5) = (40.9 + 12.2 + 4.35)/N_S = 0.823$ where $N_S = 69.8$.

The remaining 18% or so of sag events that cannot be ridden through consist of sag magnitudes deeper than 0.6 p.u. and those shallow sags of long durations.

Thus, with this selection of C_{DC} , it is seen that the SPVG is capable of helping the downstream load to ride through more than 82% of the voltage sags recorded in [41] for nighttime.

This is based on the rated apparent power capacity of the inverter is some 40% of the load rated power. It can be readily shown that the ability of voltage restoration afforded by the SPVG will increase with its apparent power rating.

3.6.2. Simulation Results

An extensive series of simulation study of the SPVG and its control system has been performed under the MATLAB/Simulink platform, with the view to assess the SPVG dynamic performance.

Fig. 3.18 shows the simulation results of V_S , V_L , I_i and V_i under a particular steady-state condition. The THD of V_S is 30%. THD of V_L and I_L are seen to have been drastically reduced to 3% and 0.5% respectively through the actions of the SPVG.

Based on the analysis method of Section 3.3 and assuming a strong upstream source, the deepest voltage sag which can be mitigated by the SPVG corresponds to the case when $V_S = 0.6$ p.u. To cater for nighttime as well as high solar insolation conditions, this study examines load ride-through capability afforded by the SPVG for P_i in the range of $-0.2 \leq P_i \leq 0.31$ p.u. Setting negative limit on P_i allows the SPVG to absorb power from the grid and maintain V_{DC} at preset level during nighttime. With the study, the designed SPVG has the parametric values shown on Table A.1. Maximum power that can be injected during normal source voltage is 0.31 p.u. (i.e. 129.6 W). The simulation study was carried out for various conditions of voltage sag/swell and insolation conditions.

Fig. 3.18 Simulation results of SPVG under steady-state condition when THD of V_s is 30%.: (a) Source voltage, (b) Load voltage, (c) Load current, (d) Injected voltage.

In this section, the results corresponding to sag of 0.6 p.u. and swell of 1.25 p.u. have been shown when $P_i \approx 42$ W. These conditions were chosen so that comparison with the corresponding experimental results can be made in the next chapter. Fig. 3.19 shows the simulation results obtained for the case of 500 ms 0.6 p.u. sag. It shows that V_L during sag has been successfully maintained with the help of the designed SPVG. The energy stored in C_{DC} compensates for the shortfall of active power. Fig. 3.19 (a) has been amplified to show the presence of the 100-Hz ripple in the DC-link voltage. The studied SPVG is a single-phase unit and as it transfers power to the external system, it induces in the DC link voltage ripples of some 0.3 V.

Fig. 3.19(a) shows the DC-link voltage begins to drop due to discharging the ESS. After the sag is over, V_{DC} begins to recover.

Fig. 3.19 Simulation results of SPVG for a 60% sag (deepest voltage sag) and when $P_i \approx 42$ W: (a) DC-link voltage (b) supply voltage; (c) Load voltage; (d) Injected voltage; and (e) Injected active and reactive power

Simulation results of 1.25 p.u. swell are shown on Fig. 3.20. When the swell occurs, active power injection from the SPVG is stopped and P_{PV} is diverted to C_{DC} . Hence, there is a corresponding rise in V_{DC} .

Transient responses of the SPVG were obtained and shown in Fig. 3.21 for a 60% voltage sag when the irradiance is very low ($P_i \approx 4$ W). In this figure, instead of showing the complete 500-ms event, only the initial 3-cycles or so of the behavior of the system following the incipient of the sag is shown. The total reaction time required for the SPVG to mitigate the sag and adjust active and reactive powers is estimated to be between 1.5~2 cycles. The simulation results indicate the load

Fig. 3.20 Simulation results of SPVG for a 125% swell and when $P_i \approx 42$ W: (a) DC-link voltage (b) supply voltage; (c) Load voltage; (d) Injected voltage; and (e) Injected active and reactive power.

voltage is recovered within few milliseconds (about half cycle). The voltage transient is damped very effectively such that a negligible level of oscillations appears in the load and injected voltages. The advantage of the capacitor energy storage device in enhancing the performance of the SPVG has also been clearly verified because in this example, although the level of P_{PV} is very low and it is not sufficient for successful voltage sag mitigation, the SPVG could effectively maintain the load voltage using the energy stored in C_{DC} .

Fig. 3.22 shows the operation of SPVG under fast variation of irradiance under no grid fault condition. Irradiance changes from 300 W/m^2 to 1000 W/m^2 within 3 sec and after 1 sec, it returns back to 300 W/m^2 . The SPVG is seen to successfully

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regulate the load voltage by adjusting the injected active and reactive power. The load voltage magnitude is almost constant, as shown in Fig. 3.22(c). As shown in

Fig. 3.21 Simulation results of SPVG for a 60% sag (deepest voltage sag) and very low irradiance $P_i \approx 4$ W: (a) supply voltage; (b) Load voltage; (c) Injected voltage; and (d) Injected active and reactive power.

Fig. 3.22 Simulation results of SPVG for dynamic variation of irradiance : (a) Irradiance; (b) photovoltaic power; (c) Load voltage magnitude; (d) Injected active and reactive power; (e) DC-link voltage.

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Fig. 3.22(a) and (b), the MPPT scheme could track the changes in irradiance effectively and rapidly. Disturbances of about 5~6 V on V_{DC} due to fast variation of insolation have been observed in Fig. 3.22(e). Theoretical evaluation of the steady state error of load voltage is 0.12% and simulation results show that it is less than 0.2%.

The stability of SPVG when the irradiance suddenly changes from 0 to 1000 W/m² was also studied. Fig. 3.23 shows the response of the SPVG under the step change of irradiance condition. As shown in Fig. 3.23(a) and (b), the MPPT scheme tracks the irradiance step changing and within 2 sec, it can again reach maximum power point.

Fig. 3.23 Simulation results of SPVG for irradiance step change: (a) Irradiance; (b) photovoltaic power; (c) source voltage; (d) Load voltage; (e) Injected voltage; (f) Injected active and reactive power.

3.7. Conclusions

A series-connected solar power harnessing system termed SPVG has been examined. While the primary function of the SPVG is to maximize solar energy harness to meet load demand, the device has the added function to improve voltage quality at the downstream load terminal. Voltage quality is enhanced as solar insolation varies as well as under upstream disturbance conditions.

Using the steady-state model of the SPVG, analytical expressions governing power flows of the device have been derived. Operating characteristics of the SPVG have been examined through which control strategies for maintaining load voltage have been developed, including those situations of upstream voltage sags/swells. From the derived feasible operating state of the SPVG, it is established that for a given voltage sag, there exists a minimum active power injection level below which load ride-through will not be possible unless an energy storage system is used to provide the shortfall in power. The minimum required capacitance of the DC-link capacitor ESS to achieve ride-through for the given load and inverter power ratings can also be determined. Stability analysis of the proposed closed-loop control scheme provides useful information on the design of the inverter controller.

The results of the analytical work are supported by an extensive series of simulation studies. The simulations demonstrate clearly the SPVG performs as predicted by the analytical model in mitigating voltage sags/swells. The beneficial effect of the capacitor energy storage device in enhancing the performance of the SPVG has also been clearly demonstrated.

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4.1. Introduction

The purpose of this chapter is to validate the proposed series-connected photovoltaic generator (SPVG) system described in Chapter 3. To demonstrate the effectiveness of the proposed system, a prototype of the SPVG has been constructed and tested in the author's laboratory. The SPVG prototype consists of a full-bridge bidirectional inverter, a boost converter, programmable AC source (Chroma-61511), IGBT gate driver boards, photovoltaic modules, DC power supply, digital controller, two current-transducers, four voltage-transducers and an interface circuit. Tests were carried out under the normal grid condition, as well as under voltage sag and swell, at various P_{PV} . In the following sections, the hardware configuration of SPVG is explained and the experimental results pertaining to the steady-state and voltage sag/swell conditions are reported. Grid synchronization methods are also described.

4.2. Hardware System Description

In order to implement the control system, a digital signal processor (DSP) controller board (DS 1103) platform with MATLAB/Simulink in Real-Time Interface (RTI) has been used. The dSPACE is also equipped with ControlDesk 3.7 which allows electrical parameters to be recorded during tests. An Intel core i5 CPU 2.8 GHz personal computer is used to communicate between the DSP processor board and the user. The experimental setup is shown in Fig 4.1. The schematic diagram of the hardware laboratory prototype is shown Fig. 4.2. Details of the hardware are as follows.

4.2.1. dSPACE Controller Board

Fig. 4.3 shows the block diagram of the DS1103 controller board. It provides several interface connections. DS1103 includes 20 channels of 16-bit ADC, 8 channels of

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Fig. 4.1 Experimental set-up of the SPVG

Fig. 4.2 Schematic of the laboratory hardware prototype of the proposed SPVG.

16-bit DAC, 7 channels of digital input incremental encoder subsystem and 4 channels of 8-bit digital I/O ports. Local memory is a 32 MB application synchronous dynamic random access memory (SDRAM) and global memory includes a 96 MB communication SDRAM for data exchange with host and also for

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Fig. 4.3 Block diagram of DS1103 controller board.

data storage purposes. For additional I/O tasks such as PWM pulse generation, A/D and I/O, an independent slave DSP controller (Texas Instruments TM320F240 DSP) has been utilized as a subsystem. The control board can be programmed by Simulink software environment. The dSPACE interface software can access to measured parameters, thus monitoring, recoding and setting of control software are allowed. Additional details of DS1103 have been illustrated in Fig. 4.3.

4.2.2. Programmable AC Source

A 12-kVA programmable AC Source (Chroma-61511) is used as the main power supply. The AC power supply can be programmed to generate various sag/swell in terms of magnitudes and durations, and/or distorted supply voltage of specific THD.

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4.2.3. Voltage Source Inverter

A bi-directional full-bridge single phase inverter has been constructed for the SPVG. Fig. 4.2 shows the inverter hardware arrangement. Two insulated gate bipolar transistor (IGBT) SEMIKRON modules SKM 75GB123D are used in the inverter circuit. The schematic diagram of half bridge IGBT module is shown in Fig. 4.4. The rated voltage and current ratings of this IGBT module are 1200 V and 75 A respectively. Fig. 4.4 shows the connection diagram of the IGBT module.

Fig. 4.4 SEMIKRON SKM 75GB123D IGBT module.

4.2.4. PV Modules

In order to perform the experiments, 5 PV panels had been utilized. The PV modules were connected in series to provide suitable V_{PV} for the SPVG. The specifications of each PV module are: rated power = 45W, $V_{OC} = 18V$, $I_{SC} = 3.4A$ at 25°C. The PV modules were installed next to the Electric Power Research Laboratory of the School of EEE, NTU located at 1°20'32.0"N, 103°40'49.3"E.

Fig. 4.5 Schematic diagram of series-connected PV modules.

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4.2.5. DC/DC Converter

A DC/DC boost converter is used to control the power flows between the PV modules and inverter. This DC/DC converter is shown in Fig. 4.2. The IGBT used in this converter is the same as that in the inverter. The parametric values of the converter components correspond to those presented in Table A.1.

4.2.6. IGBT Gate Drivers

Two SEMIKRON SKHI23/12 driver boards are used for driving the inverter switches. Fig. 4.6 shows the schematic diagram of SKHI23/12 IGBT gate driver. Each gate driver is utilized to fire the IGBT gates of the same arm of the inverter. In order to prevent IGBTs of the same arm being in the “on” state at the same time, an interlock circuit is utilized in the gate driver board. It prevents one IGBT turning-on before another IGBT gate charge is completely discharged. The interlock-time can be adjusted to provide a safe margin between the switching of the two IGBTs in a half-

Fig. 4.6 Schematic diagram of SKHI23 gate driver board.

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bridge.

For the boost converter, a SEMIKRON SKHI10/12 is used to drive the IGBT switch. Fig. 4.7 depicts simplified block diagram of the SKHI10 board. Turning on output gate voltage $V_{G(on)}$ is equal to +15 V and switching off voltage $V_{G(off)}$ is -8 V.

Switching speed of each IGBT depends on the value of gate resistors R_{Gon} and R_{Goff} shown in Fig. 4.7. This is because during the charging and discharging of the IGBT input capacitance, these two resistors determine the time of charging and discharging. Also, the charging/discharging depend on several parameters such as stray inductance of the circuit, switching frequency, DC-link voltage and type of IGBT.

SKHI10/12 and SKHI23/12 are equipped with short circuit protection which monitors the collector to emitter voltage V_{CE} . When a fault occurs, the protection circuit turns off the IGBTs and activates ERROR signal (pin 3 of SKHI10 or pin x1.3 of SKHI23). The ERROR signal can be used to turn off the PWM signals of controller and prevent the gate driver repeated switching under fault condition. The SKHI gate driver boards are designed to accept two different logic input voltage

Fig. 4.7 Schematic diagram of SKHI10 gate driver board.

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levels. The factory setting is CMOS (+15 V). This voltage level is preferred for noisy environment and long connection between control circuit and SKHI board. Another setting is TTL- HCMOS (+5 V). This level is suitable for low power applications and short connection between driver and control system. In this prototype, CMOS logic level is used. The manufacturer recommended value of gate resistors is $22\ \Omega$ for the SKM 75GB123D IGBT module.

4.2.7. Voltage Measurement Boards

The Hall Effect voltage transducers (LEM LV25-P) are used to measure the source, load, PV module and DC-link voltages. In order to adjust voltage measurement range, an external resistor (R_1) must be inserted in series with the input terminal of the transducer in the primary circuit. The Hall Effect transducer provides an output current of between -20 to 20 mA which is proportional to the measured voltage. As DSP circuit accepts voltage signal and in order to send the measured signal to the DSP A/D channel, the secondary current is converted to voltage between -10 to 10 V using an appropriate resistor R_M . Fig. 4.8 shows the schematic diagram of the measurement unit.

Fig. 4.8 Schematic diagram of voltage measurement unit using LEM voltage transducer.

Fig. 4.9 Schematic diagram of current measurement unit using LEM current transducer.

4.2.8. Current Measurement Boards

Fig. 4.9 shows the schematic diagram of the measurement unit. The Hall Effect current transducer (LEM LA 55-P) measures primary current (I_p). Secondary current (I_s) is proportional to the primary current. As mentioned in Section 4.2.7, analog inputs of the DS1103 accept only voltage signals. Therefore the secondary current is transformed to voltage using the resistor R_M . The voltage across the resistor must be limited between ± 10 . This voltage is measured by an A/D board.

4.2.9. DC-link Capacitor

The capacitance of the DC-link capacitor was determined in Chapter 3. The selection of C_{DC} depends on sag magnitude and duration, nominal DC-link voltage, minimum DC-link voltage and the rating of the load. The selected capacity of C_{DC} is 7 mF. It is made up of a 6mF capacitor in parallel connection with another 1 mF capacitor.

4.2.10. Inverter Output Filter

A filter is connected to the inverter output to reduce high frequency switching harmonics. The LC filter is selected and in conjunction with inductance of

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transformer, they forms a LCL filter. To improve the damping of the filter a damping resistor is connected in series with filter capacitor, as shown in Fig. 4.2.

4.2.11. Interface Circuit

The binary output of the DSP controller board (DS1103) is a TTL signal (5V). In order to use the digital outputs of the dSPACE for PWM switching, the TTL voltage level must be shifted to CMOS logic level (15 V). The MC14504B level shifter is used to shift the TTL signal to CMOS logic level. Fig. 4.10 shows the logic diagram and mode selection table of the IC. By the appropriate selection of the operation mode of V_{CC} and V_{DD} according to Fig.4.10, the interface from CMOS to CMOS at one logic level or from TTL to CMOS is allowed. Mode 1 has been used in the implemented circuit.

4.3. Voltage Grid Synchronization in Normal and Fault Condition

In order to achieve fast dynamic response and effective voltage disturbance compensation during low-voltage ride-through (LVRT), the synchronization of injected current and voltage into the grid plays a crucial role in the SPVG control

Fig. 4.10 Logic diagram of level shifter.

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system. This section intends to discuss the synchronization technique under the normal operating condition and LVRT. Any delay in sensing the grid voltage magnitude and its phase angle will result in a delay in the ride through of low voltage incident. Furthermore, the response to variations in the load or grid voltage is highly influenced by the delay of its measurements.

A suitable synchronization system should detect the grid state rapidly and precisely when a disturbance occurs. In connection of a grid-tied converter, grid synchronization is important since knowing the grid voltage magnitude and phase angle makes the regulation of active and reactive power possible. Furthermore in three-phase systems, the information about grid phase angle and frequency is essential to transform parameters from natural reference frame to the synchronous reference frame. This transformation makes it possible to deal with the measured currents and voltages in the form of DC variables in the control system.

Many synchronization methods to detect the phase angle have been reported in the literature for single and three phase systems [21, 35, 214-227]. In general the approaches can be divided into two main categories:

- a) **The frequency-domain synchronization methods:** these techniques are mostly based on discrete versions of Fourier transform. Discrete Fourier Transform (DFT) and the recursive discrete Fourier transform (RDFT) are two possible methods for grid synchronization for power converters. More details can be found in [35, 225-227].

Application of DFT in identifying the harmonic components of grid voltage and current is a well-established method in power quality studies. The main idea is using the DFT technique to extract the fundamental frequency component of the grid voltage to synchronize converters to the grid [225, 226]. Due to the computational burden of the DFT, implementation of this method on some types of digital controllers is rather difficult. Thus RDFT approach is proposed to reduce the computational burden of fundamental frequency detection [225, 228].

- b) **The time-domain synchronization methods:** the most well-known method of this group is the phase-locked loop (PLL). In this method, an internal oscillator is enabled in an adaptive loop to follow the grid voltage to generate an amplitude and phase-coherent internal signal. The frequency-locked loop (FLL) is another synchronization technique which is very effective when the grid voltage is affected by grid disturbances.

4.3.1. Application of PLLs in Power Converter Synchronization

The zero crossing method is the simplest synchronization method but its performance in highly distorted signals is not satisfactory due to multiple zero-crossing occurrences and inaccuracy. Even though some modified zero crossing techniques have been presented, they may still be influenced by frequency variations or low frequency harmonics [35].

There are many types of PLL reported in the open literature. Fig. 4.11 shows a basic structure of a conventional PLL. It consists of three main fundamental blocks: phase detector (PD), loop filter (LF) and voltage-controlled oscillator (VCO). PD generates a signal proportional to the phase difference between the input signal v_s and the signal generated by the VCO. VCO is a linear integrator [35, 38]. LF is typically a first order low-pass filter or a PI controller to attenuate the high-frequency components originated from the PD output. VCO generates an AC signal that its frequency is shifted with respect to a given central frequency, ω_c , as a function of the input voltage provided by the LF [35]. Different techniques are presented in the literature to implement each of the blocks of a PLL.

In this research project, the focus is on the single phase application of PLL in grid synchronization of single PV inverters thus the commonly used PLL will be briefly described.

The T/4 delay PLL is one member of Park transform family of PLLs [21, 35, 38, 222]. In this PLL the orthogonal component is obtained by making T/4 delay

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between input signal and the quadrant signal (i.e. $\pi/2$ phase shift). Fig. 4.12 shows the block diagram of PLL.

Fig. 4.11 Basic block diagram of a conventional PLL

Fig. 4.12 Structure of the T/4 delay PLL

In the Enhanced PLL, an adaptive notch filter (ANF) is added to PD of conventional PLL. Fig 4.13 shows the diagram of EPLL. If the phase angle of input signal and reference signal from VCO become equal, then the output of the ANF tends to zero and consequently, the output signal of PD becomes oscillation free. The output of PD is fed to conventional PLL to detect input phase angle. One of the advantages of EPLL compared to conventional PLL is that the desired output of filter estimated signal is locked both in phase and in amplitude of the input signal. The speed of

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estimation depends very much on the filter parameter k and therefore, k should be tuned appropriately [35, 229, 230].

Fig. 4.13 Enhanced PLL

The second-order generalized integrator-based PLL (SOGI-PLL) is an adaptive filtering based PLL. SOGI is used to form an orthogonal signal generator (OSG) [35, 38, 218, 231, 232]. OSG generates quadrant signals in the PD unit of the PLL. The Park transform can be applied to the output of OSG to transform the signals to dq rotating frame. Then the error of the PD is fed into the LF and the result is fed to the VCO [35, 38]. Fig. 4.14 shows the block diagram of SOGI-PLL. The bandwidth of the SOGI-based adaptive filter is a function of k , thus SOGI-OSG based PLL is suitable for variable-frequency applications because the bandwidth does not depend on the center frequency ω_c .

Fig. 4.14 SOGI-based PLL

4.3.2. Comparison of the PLLs

These above-mentioned synchronization techniques for single phase application are compared during LVRT, frequency jump and phase jump in terms of the settling time and the overshoot of frequency [38]. The performances of these PLLs are not very satisfactory during LVRT operation because they cannot detect the sag events very quickly. Thus in order to improve the performance of PV inverter under LVRT situations, it is necessary to deploy a fast sag detection method. The T/4 delay PLL can track the amplitude change quickly in about 5 ms, but it cannot provide accurate grid phase synchronization when the grid frequency is varying. EPLL can estimate both the amplitude and the frequency of the input voltage but it shows transient variations. In the direct instantaneous power control scheme, this PLL can be used because it is not using OSG concept [38, 233]. The transient response of SOGI-OSG PLL is better than the T/4 delay PLL and EPLL, particularly during frequency variations/jump. SOGI-OSG is suitable for grid synchronization if it is associated with fast detection unit [38, 186]. Therefore in this research work, SOGI-OSG and DFT have been utilized for grid system synchronization and source voltage parameters detection.

4.4. Control System Implementation

The control system of the SPVG is accomplished in MATLAB/Simulink environment and then it was converted to C codes and loaded to the DS1103 controller board. The interface between hardware and Simulink software is linked by real time interface (RTI) software. The RTI toolbox provides specific blocks in Simulink environment, which allows the linkage between Simulink and the DS1103 hardware. Fig. 4.15 shows the Simulink block diagram of the SPVG control system. Six A/D channels are used to acquire the analog system parameters, which are carried out by 2 MUX ADC blocks. In order to obtain actual measured values, the outputs of MUX ADC channels are multiplied by scaling factors. To adjust the scaling factor of each measurement unit, the transducers have been tested in the laboratory by injecting voltage/current test signals and comparing the results with

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Fig. 4.15 Simulink block diagram of SPVG overall control system.

calibrated multi-meters. In order to adjust the output of the measurement unit when the input signal is zero, certain small DC bias is added to the output signal.

The sampling time of the DSP is set to 32 μ sec. The reference load angle θ is calculated with the aid of measured source voltage, load voltage and current. Thereafter the reference load voltage is calculated according to the method explained in Chapter 3. Then the reference voltage is sent to the PWM generation block in Simulink software. The generated PWM pulses are fed to the binary output of DS 1103. The binary signals are shifted from TTL to CMOS using interface circuit, as explained in Section 4.2.11. Output signals of the interface are fed to the IGBT gate driver boards.

4.5. Steady-state Operation

Extensive test measurements have been carried out under the normal source condition, i.e. $V_S = 220$ V. The first three channels of Fig. 4.16 shows a sample of the recorded waveforms of V_S , V_L and V_i .

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It has been observed the total harmonic distortions (THD) of V_L and V_i are 1% and 4% respectively. Their distortion levels are considered within acceptable limits. The recorded V_{DC} has been processed to show the presence of the 100-Hz ripples, as can be clearly seen in Fig. 4.16(d). The magnitude of the ripples is less than 0.3 V peak.

Fig. 4.16 Experimental results at steady state normal grid condition captured on an oscilloscope (a) Supply voltage: ch1. (b) Load voltage: ch2. (c) Injected voltage: ch3. (d) Filtered 100 Hz AC ripple at V_{DC} : ch4.

Fig. 4.17(a) and (b) show the recorded waveforms of V_S , V_L , I_i and V_i and their respective harmonic spectrums when the THD of V_S is 30%. However, THD of V_L is seen to have been drastically reduced to 3~4% through the actions of the SPVG. Fig. 4.17(c) and (d) show the recorded results when the THD of V_S is 19%. Further experimental measurements revealed that the THD of V_L increases by about 1% when the feedforward control loop shown in Fig. 3.4 has been omitted.

Fig 4.18 shows the experimental results without the feedforward control loop. Thus these test results have verified that the SPVG is effective in reducing the harmonic distortions in V_L . The experimental results indicate that the steady state error is less than 1.0% in both cases.

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Fig. 4.17 Experimental results under steady-state condition: ch1: Source voltage, ch2: Load voltage, ch3: Load current, ch4: Injected voltage. When THD of V_S is 30%. (a) Wave forms (b) harmonic spectrum. When THD of V_S is 19%. (c) Wave forms (d) harmonic spectrum.

Fig. 4.18 Experimental results under steady-state condition: ch1: Source voltage, ch2: Load voltage, ch3: Load current, ch4: Injected voltage. When THD of V_S is 30% and without using feed-forward loop (a) Wave forms (b) harmonic spectrum.

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The effectiveness of the SPVG under the proposed control scheme for voltage quality enhancement has been compared against that under constant power factor operation of the PV system. From the series of steady-state measurements carried out under normal grid condition, a typical set of the recorded results has been chosen and shown in Fig. 4.19. Fig. 4.19(a) shows V_L is unable to remain constant even under relatively constant P_{PV} when the SPVG is operating at the fixed power factor of 0.98 lag. In contrast, Fig. 4.19(b) shows that under the proposed voltage control scheme, V_L hardly varies even as P_{PV} changes by some 0.1 p.u. over the 10-min recorded period.

Fig. 4.19 Experimental results obtained at steady state normal grid condition: Load voltage and corresponding P_{PV} under (a) fixed power factor and (b) voltage control modes.

4.6. Dynamic Performance of the SPVG

In this part of the test validation, voltage sags and swells were generated using the 12-kVA Programmable AC Source (Chroma-61511). The rating of the load is only 3.6% of the source rating and therefore, the AC source can be considered a strong upstream system.

Fig. 4.20(a) shows V_{DC} , V_S , V_L and V_i captured on an oscilloscope when a 500 ms 60% voltage sag occurs. During the sag, V_{DC} decreases to approximately 157.5 V before it starts to recover after the sag event. P_i during sag is about 133 W, which is in close agreement with the simulation results shown in Chapter 3 and in line with

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Fig. 4.20 Measured results of SPVG for a 60% sag and when $P_i \approx 42$ W. (a) DC-link voltage, supply voltage, load voltage, injected voltage captured by oscilloscope and the expanded plot; (b) Injected active and reactive powers recorded by dSPACE software.

the results of the theoretical analysis presented of Chapter 3. Post-sag P_i is lower than that before the sag as some of P_{PV} has been diverted to re-charge C_{DC} .

Fig. 4.21 shows the dynamic response of the SPVG during a 1.25 p.u. voltage swell. As explained in Chapter 3, P_i reduces to zero and the SPVG absorbs reactive power during the swell. The surplus power P_{PV} is stored in C_{DC} and consequently V_{DC} increases, as indeed shown in the figure. From the P_i - Q_i test results, the total reaction for the SPVG to mitigate the sag is estimated to be between 1.5~2 cycles. This is an encouraging performance as it compares favorably to the 4~5 cycles reaction time shown on the single phase photovoltaic system reported in [38].

The experimental results point out the load voltage is recovered without any significant oscillations. The steady state error is about 1%. The expanded plots in Fig. 4.20 and 4.21 also show that there is hardly any discernible changes in $v_L(t)$ throughout the complete sag/swell events.

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Fig. 4.21 Measured results of SPVG for a 125% swell and when $P_i \approx 42$ W. (a) DC-link voltage, supply voltage, load voltage, injected voltage captured by oscilloscope and the expanded plot; (b) Injected active and reactive powers recorded by dSPACE software

As the 100-Hz ripple in V_{DC} is expected to be less than 0.3 V peak, the presence of the ripples is also not discernible in V_{DC} as V_{DC} was measured using 100V/div scale.

By comparing the test results shown in this section with those obtained from simulation and included in Chapter 3, it can be concluded that the two sets of results agree remarkably well. Minor differences in the two sets of results are due to the inaccuracies in the modeling of the source impedance as well as the imprecise values used to represent the inductances of the injection transformer. Also P_{loss} in practice depends on several factors but in the simulation, this has been accounted for by adjusting the resistance inside the IGBT model and the internal losses of the transformer. For example, during the 0.6 p.u. voltage sag, there was some 7~9 W difference between the P_i values shown in the simulation and the experimental measurements; V_{DC} in the simulation was about 3 V more than that obtained in the experiment. Notwithstanding these discrepancies, the simulation and test results are considered sufficiently conclusive in showing the efficacy of the proposed SPVG.

4.7. Conclusions

In order to evaluate the effectiveness of SPVG a hardware test setup has been implemented in the author's laboratory. The results of the analytical work are supported by the experimental test measurements. The simulation results presented in Chapter 3 and the experimental test results demonstrate clearly the SPVG performs as predicted by the analytical model in mitigating voltage sags/swells. The beneficial effect of the capacitor energy storage device in enhancing the performance of the SPVG has also been clearly demonstrated. It was shown that SPVG is able to assist with load ride-through against upstream grid disturbances. Also it can maintain the load voltage constant during power fluctuation of intermittent solar irradiance.

Based on the results obtained in Chapters 3 and 4, it is clear the proposed SPVG can indeed improve power quality which can thus lead to economic benefits due to the improved security of supply. However, it is not clear whether the improved quality of supply can be achieved by designing SPVG of reasonable cost. The subsequent chapters are intended to provide answer to this question.

Chapter 5. A Statistical Approach to Determine the Energy Storage Capacity of the Series-connected PV Generator

5.1. Introduction

The use of series-connected PV system for improving power quality was considered in Chapter 3 and reported in [14, 181]. The voltage disturbances and solar insolation were treated as deterministic events in [14, 181]. However the stochastic nature of the voltage disturbances, load demand and solar insolation level will greatly impact the voltage enhancement ability of the PV-generator system. Therefore to evaluate the load low voltage ride through (LVRT) capability of SPVG using deterministic methods is not suitable. In this chapter, the statistical information of the load, solar insolation level and voltage disturbances are considered when evaluating the capability of the PV-generator in enhancing voltage quality.

In the considered topology of the series-connected photovoltaic generator (SPVG) shown in Fig. 5.1, a power decoupling electrolytic capacitor (C_{DC}) is installed between the two conversion stages of the SPVG. C_{DC} reduces the voltage ripple in the DC-link and acts as an energy buffer. As shown in Chapter 3, C_{DC} plays an important role in the voltage quality enhancement function of the SPVG. Unfortunately, current ripples originated from the inverters and capacitor current harmonics generate heat which in turn, accelerates the degradation in the energy storage capability of the electrolytic capacitors [234-236]. Thus, another aspect of the present investigation is to also consider the aging effect of C_{DC} on the load LVRT performance of the SPVG. Accordingly, Section 5.2 provides a brief description of the SPVG. Section 5.3 examines the ageing effect of electrolytic capacitor, expressed in the form of equivalent series resistance (ESR), on the load LVRT. Section 5.4 contains the proposed statistical method to assess the ability of the SPVG in load voltage quality enhancement. Laboratory test results to validate the analysis are

Fig. 5.1 (a) Schematic diagram of the SPVG in a grid system. (b) Corresponding phasor diagram of the SPVG.

shown in Section 5.5. Numerical examples are given in Section 5.6 to illustrate the proposed design technique.

5.2. Analysis and Control of SPVG Operations

5.2.1. System Description and Problem Statement

The schematic diagram of the SPVG is shown in Fig. 5.1. As mentioned before, in the present investigation, only single-phase SPVG is considered. The corresponding phasor diagram is also shown in Fig. 5.1(b).

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When the grid system is under normal state, the PV modules are assumed to operate under the maximum power point (MPP) state. Fig. 5.1 shows the conversion of the photovoltaic power P_{PV} to P_i through a DC-AC inverter. P_i is the power injected into the external grid-load system. At any given time, P_{PV} depends on the solar insolation level and the operating temperature of the PV modules [203]. The analytical solution described in [201] is used in this investigation to determine the MPP state of P_{PV} , based on the PV cell equivalent circuit parameters. While the DC-DC converter is used to achieve MPP tracking, the inverter regulates the complex power flow $P_i + jQ_i$ to the grid. In order to achieve maximum utilization ratio, voltage ripples at the output of the PV modules must be limited. The capacitor (C_{PV}) is therefore added to reduce the ripples [149]. As mentioned before, C_{DC} can be utilized as an energy storage device during grid voltage disturbance and this function will be examined later. The role of the LC-filter is to reduce voltage harmonics at the output of the inverter.

The SPVG may also include an injecting transformer to boost the voltage of the inverter and to provide the galvanic isolation. In order to avoid modeling complexity, an ideal 1:1 isolating transformer is assumed in the following analysis.

While the PV modules operate under MPP state, variations in the solar insolation level will in turn cause deviations in P_i . In addition, another possible source of voltage disturbance is due to switching or fault occurrences in the upstream grid system. Such a disturbance can be viewed as a sudden change in $\bar{V}_S$. Regardless of the cause of the voltage disturbance, the main function of the SPVG is to operate at MPP to maximize the solar energy harness, while at the same time, its inverter control system must manipulate the output reactive power Q_i so as to maintain the magnitude of $\bar{V}_L$ constant, although the voltage phase angle θ is allowed to change.

5.2.2. Role of SPVG on Enhancing Load Voltage Quality

According to the control strategy of the SPVG as explained in Chapter 3, consider the steady-state operation of the power system shown in Fig. 5.1. Assuming a stiff grid network, $\bar{V}_S \approx \bar{E}_S$ as Z_S is negligible in comparison with the load impedance. For given upstream grid and load system, V_S , P_L , Q_L and S_L are assumed known. At a

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given insolation level, P_{PV} is also known. As the SPVG is to regulate Q_i to maintain a constant V_L while θ can vary, so the remaining unknown parameters are θ and Q_i . θ and Q_i can be determined based on (3.20) and (3.21) presented in Chapter 3. The respective equations are

$$\theta = -\arccos\left(\frac{V_L(P_L - P_i)}{S_L E_S}\right) + \varphi \quad (5.1)$$

$$Q_i = Q_L - E_S \frac{S_L}{V_L} \sin(\varphi - \theta) \quad (5.2)$$

As explained in Chapter 3, for the successful restoration of load voltage to V_L and for a given voltage level $E_S (= V_S)$, P_i has to be at least equal to the minimum value $P_{i,min}$ given by

$$P_{i,min} = P_L - V_S \frac{S_L}{V_L} \quad (5.3)$$

$P_{i,min}$ can be readily determined for a given steady-state condition. However, at nighttime or during instances of low solar-insolation, P_{PV} can be lower than $P_{i,min}$. In which case, the SPVG will be unable to provide enough injected power for maintaining the voltage unless one makes use of the energy stored in the capacitor C_{DC} : The stored energy is to be extracted to provide the shortfall $P_{i,min} - P_{PV}$. When this occurs, C_{DC} discharges which in turn, causes V_{DC} to decrease. There is, however, a limit on how much V_{DC} can decrease to if over-modulation of the PWM generator in the inverter is to be avoided. The minimum V_{DC} when SPVG supplies $P_{i,min}$ can be determined, as follows.

Set $P_i = P_{i,min}$ and with known $P_L + jQ_L$, and θ is determined from (5.1). Denote the magnitude of $\bar{V}_L$ to be maintained as $V_{L,n}$. Hence, $\bar{V}_L = V_{L,n} \angle \theta$. Thus, from Fig 5.1 and by applying KCL at the output terminal of SPVG, the SPVG inverter output current for the given $P_{i,min}$ is

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$$\bar{I}_{inv,min} = \frac{P_L - jQ_L}{\bar{V}_L^*} + \frac{\bar{V}_L - \bar{V}_S}{-jX_{Cf}} \quad (5.4)$$

Using (5.4), the corresponding inverter output voltage $\bar{V}_{inv,min}$ is

$$\bar{V}_{inv,min} = \bar{I}_{inv,min} \times jX_{Lf} + \bar{V}_L - \bar{V}_S \quad (5.5)$$

X_{Cf} and X_{Lf} denote the reactances of C_f and L_f respectively. To avoid over-modulation in the inverter, it is necessary $V_{DC} \geq \sqrt{2} V_{inv,min}$. Thus, the minimum DC-link voltage ($V_{DC,min}$) when $P_{i,min}$ is injected into the circuit by the SPVG is

$$V_{DC,min} = \sqrt{2} V_{inv,min} \quad (5.6)$$

Using (5.3), (5.4) and (5.5), $V_{DC,min}$ can be obtained.

5.2.3. Impact of SPVG Inverter and C_{DC} Losses on Load LVRT

Another new development in the present work is to take into consideration losses in the DC/AC power conversion stage when evaluating the load LVRT enhancement ability afforded by the SPVG. During steady state, denote the losses in the DC/AC conversion circuit as P_{loss} , such that

$$P_{PV} = P_i + P_{loss} \quad (5.7)$$

where

$$P_{loss} = P_{loss,inv} + P_{loss,C} \quad (5.8)$$

In (5.8), P_{loss} is shown to consist of power losses in the inverter and that in C_{DC} . As the SPVG is connected in series to the load, therefore for a given load power, I_i is

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constant even though P_i and Q_i would vary with P_{PV} . Thus one may assume that for a given load power, the inverter loss $P_{loss,inv}$ is proportional to the load power. This assumption has been validated in the author's laboratory by measuring $P_{loss,inv}$ at a number of solar insolation and load operating conditions. For example, using the SPVG prototype described in Section 5.4, for a load power of 323 VA, 0.8 lagging power factor, $P_{loss,inv}$ was measured to be almost constant at 24~25 W even when P_{PV} varied between 0 - 175 W. However, the loss $P_{loss,C}$ in C_{DC} involves a number of factors and it shall be discussed in greater details in the next section.

The impact of P_{loss} on load LVRT can be examined in the following way. One most severe disturbance is an upstream fault but the fault is usually so short that one can expect negligible change in the solar insolation level over the duration of the fault. Hence P_{PV} can be assumed to be constant during the fault event. Such a disturbance event k yields a given voltage $V_{S,k}$ and based on the analysis of Section 5.2.2, the corresponding minimum power $P_{i,min,k,m}$ required to achieve load LVRT can be calculated. If the harnessed solar power at that instance, denoted as $P_{PV,l}$, is such that $P_{PV,l} \geq P_{i,min,k,m} + P_{loss}$, then the harnessed solar power is sufficient to support the load LVRT. However, if $P_{PV,l} < P_{i,min,k,m} + P_{loss}$, then energy stored in the capacitor C_{DC} will be needed to meet the short-fall $P_{i,min,k,m} + P_{loss} - P_{PV,l}$. The amount of discharged energy from the capacitor is given by $C_{DC} \times (V_{DCn}^2 - V_{DC}^2)/2$ where V_{DCn} is the nominal value of V_{DC} . As alluded to earlier, there is however a limit on how long C_{DC} can assume this role because V_{DC} must not fall below the limit $V_{DC,min}$. Thus, let t_{max} denote the maximum duration for which load LVRT can be achieved for the given voltage sag $V_{S,k}$, $P_{PV,l}$ and load $P_{L,m}$. Thus, one can conclude that

$$t_{max,k,l,m} = \begin{cases} \infty & \text{if } P_{PV,l} \geq P_{i,min,k,m} + P_{loss} \\ \frac{C_{DC}(V_{DCn}^2 - V_{DC,min}^2)}{2(P_{i,min,k,m} + P_{loss} - P_{PV,l})} & \text{if } P_{PV,l} < P_{i,min,k,m} + P_{loss} \end{cases} \quad (5.9)$$

l , k and m are indices pertaining to the respective values of P_{PV} , V_S and P_L .

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5.3. Consideration of Loss in and Ageing of C_{DC}

In this section, a method to calculate the capacitor current i_C is adopted and the internal loss of DC-link capacitor is determined. The ageing of the DC-link capacitor C_{DC} will be considered in the load LVRT capability of the SPVG.

5.3.1. Spectrum of the DC-link Capacitor Current $i_C(t)$

The loss $P_{loss,C}$ in C_{DC} is generated due to the presence of DC-link ripple current. The following procedure is adopted to calculate $P_{loss,C}$. With reference to the general technique presented in [237], $i_{DC}(t)$ shown in Fig. 5.1 for any inverter topology and under any load condition, is given by

$$i_{DC}(t) = \frac{\hat{A}_{00}}{2} + \sum_{n=1}^{\infty} [\hat{A}_{0n} \cos(n\omega_0 t) + \hat{B}_{0n} \sin(n\omega_0 t)] + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} [\hat{A}_{mn} \cos(m\omega_c t + n\omega_0 t) + \hat{B}_{mn} \sin(m\omega_c t + n\omega_0 t)] \quad (5.10)$$

The coefficients A_{ij} and B_{kl} in (5.10) can be derived using general method presented in [237] for sinusoidal-PWM (SPWM) as follows

Firstly, the harmonics created by a generalized sine-triangle PWM switching must be calculated. For a two-level VSI, the switched output phase voltages are

$$v_x(t) = V_{DC} \times S_x(t) \quad x \in \{a, b\} \quad (5.11)$$

And $S_x(t)$ denotes the PWM switching function [237] and it is given as

$$S_x(t) = \frac{1}{2} + \frac{M}{2} \cos(\omega_0 t + \theta_{ox}) + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \left[\frac{2}{m\pi} \sin\left([m+n]\frac{\pi}{2}\right) J_n\left(m\frac{\pi}{2}M\right) \times \cos\{m[\omega_c t + \theta_{cy}] + n[\omega_0 t + \theta_{ox}]\} \right] \quad (5.12)$$

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where $J_n(\cdot)$ denotes the n^{th} order Bessel function of the first kind. ω_c and θ_{cy} represent the carrier angular frequency and carrier phase angle respectively. The carrier phase shift is set to zero for two-level converters. M is the modulation index. θ_{ox} is the fundamental phase angle and will be set to 0 and π for single phase inverter legs. For a three-phase system, θ_{ox} will be set to 0, $-2\pi/3$ and $2\pi/3$. x denotes phase/leg of the converter (i.e. a, b and c).

The convolution of S_x and i_x in frequency domain results in the contribution of leg x in the DC-side current, i.e. $i_{DC,x}(\omega)$. Summation of all legs/phases contributions will result in the DC-link current $i_{DC}(t)$ (e.g. in single phase inverter $i_{DC}(t) = i_{DC,a}(t) + i_{DC,b}(t)$). The schematic diagram of a single phase voltage source inverter is shown in Fig. 5.2.

The coefficients in (5.10) for a single phase inverter are:

$$\hat{A}_{00} = \frac{M}{2} I_o \quad (5.13)$$

$$\hat{A}_{01} = 0, \hat{B}_{01} = 0 \quad (5.14)$$

$$\hat{A}_{02} = \frac{M}{2} I_o \cos \delta \quad (5.15)$$

$$\hat{B}_{02} = -\frac{M}{2} I_o \sin \delta \quad (5.16)$$

$$\hat{A}_{mn} = (1 + \cos(n\pi)) \times \frac{I_o}{m\pi} \cos\left([m+n]\frac{\pi}{2}\right) \times \cos \delta \times \left[J_{n+1}\left(m\frac{\pi}{2}M\right) - J_{n-1}\left(m\frac{\pi}{2}M\right) \right] \quad (5.17)$$

$$\hat{B}_{mn} = (1 + \cos(n\pi)) \times \frac{I_o}{m\pi} \cos\left([m+n]\frac{\pi}{2}\right) \times \sin \delta \times \left[J_{n+1}\left(m\frac{\pi}{2}M\right) + J_{n-1}\left(m\frac{\pi}{2}M\right) \right] \quad (5.18)$$

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Fig. 5.2 Single phase voltage source inverter.

$$\hat{A}_{mn} = 0, \quad \hat{B}_{mn} = 0 \quad \text{for} \quad m = 0 \text{ and } n > 2 \quad (5.19)$$

Due to the cancellation of the fundamental and triplen harmonics, $i_{DC}(t)$ contains only the DC component, second harmonics, carrier harmonics and even sidebands.

Thus, $i_{DC}(t)$ can be evaluated. Next, to simplify the analysis, assume that $I_{DC,in}$ in Fig. 5.1 includes only the DC component while harmonic flow from the DC/DC converter is negligible. Thus,

$$I_{DC,in} = \frac{P_{PV}}{V_{DC}} \quad (5.20)$$

Hence the capacitor current $i_C(t)$ can be readily calculated:

$$i_C(t) = i_{DC}(t) - I_{DC,in} \quad (5.21)$$

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The values of the coefficients $\hat{A}_{ij}$ and $\hat{B}_{ij}$ are defined by the inverter topology adopted, PWM method used, modulation index M , peak value (I_o) of the inverter current and inverter power factor $\cos \delta$ at the fundamental frequency f_o [237]. I_o , M and δ can be readily determined as follows.

$$I_o = \sqrt{2} \times I_{inv} \quad (5.22)$$

where I_{inv} is the fundamental component of the inverter current and I_o is the peak current.

Based on the definition of modulation index

$$M = \frac{\sqrt{2} \times V_{inv}}{V_{DC}} \quad (5.23)$$

Finally, let δ denote the inverter power factor angle, i.e.,

$$\bar{V}_{inv} = V_{inv} \angle \sigma_v \quad (5.24)$$

$$\bar{I}_{inv} = I_{inv} \angle \sigma_i \quad (5.25)$$

$$\delta = \sigma_v - \sigma_i \quad (5.26)$$

As an illustration of the above derivation, Fig. 5.3(a) shows the DC-link capacitor-current spectrum and calculated DC-link capacitor-current spectrum of the SPVG DC-link obtained from simulation. SPVG is assumed operating at $P_i = 100$ W and modulation frequency $f_s = 2$ kHz, and unipolar SPWM is used. Also shown in Fig. 5.3(b) is the calculated spectrum obtained using (5.13)-(5.19). As can be seen from

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Fig. 5.3 Spectrum of the DC-link capacitor current: (a) from simulation (b) from calculation using (5.13)-(5.19).

the figure, the calculated results are in good agreement with those obtained from the simulation.

5.3.2. Evaluation of Equivalent Series Resistance of C_{DC} and $P_{loss,C}$

In the equivalent circuit of the DC-link capacitor shown in Fig. 5.1, R_0 includes the resistance of the terminals, foils and tabs; R_l represents the electrolyte resistance,

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while the parallel R_2 and C_2 circuit constitutes the model of the dielectric [235]. Their parametric values can be determined from experimental measurements. Based on these circuit parameters, the equivalent series resistance (ESR) of the capacitor C_{DC} can be readily shown to be

$$ESR = R_0 + R_1 + \frac{R_2}{1 + R_2^2 C_2^2 \omega^2} \quad (5.27)$$

Equation (5.27) shows that ESR is a function of frequency $\omega = 2\pi f$. Also, i_C generates heat inside the capacitor due to the presence of the resistances and thus increases the operating temperature T of the capacitor. This in turn causes a decrease in ESR as the conductivity of the electrolyte is changed [235]. Therefore ESR is often expressed in the form $ESR(T, f)$ to signify that the ESR is a function of T and f .

In calculating $ESR(T, f)$, the internal temperature T should be known. T can be calculated using a thermal model of electrolytic capacitor [234], as follows. Let

$$T = T_{amb} + \Delta T \quad (5.28)$$

where ΔT denotes element temperature rise. ΔT is given by

$$\Delta T = \frac{P_{loss,C}}{H \times S} \quad (5.29)$$

H denotes heat transfer per unit surface area ($\text{W/m}^2 \text{ C}$). The surface area (m^2) is denoted by S . Usually the capacitor radius is larger than the radius of the internal cylindrical can element, as shown in Fig. 5.4. Therefore a dead air space exists between the external and internal cylinders. This in turn increases the air thermal resistance between the capacitor and air. This space has been considered in the heat transfer model [234], [238]. S is determined using (5.30).

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$$S = 2\pi \times (r \times z + r^2) \quad (5.30)$$

where z and r denotes the capacitor height and radius shown in Fig. 5.4.

The relevant equation (5.31) shows the heat transfer per unit area.

Fig. 5.4 Mechanical dimension of aluminum electrolytic capacitor.

$$H = \frac{G}{1 + 110 \times r \times \ln\left(\frac{r}{r_e}\right)} \quad (5.31)$$

r_e represents the capacitor element radius shown in Fig. 5.4. G denotes an experimental parameter which has been found for sleeved capacitors [238].

Then the capacitor internal power losses $P_{loss,C}$ is calculated using

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$$P_{loss,C} = \sum_{n=0}^{N_h} ESR(T, nf_0) \times I_{C,n}^2 \quad (5.32)$$

$I_{C,0}$ is the DC component whereas $I_{C,n}$ denotes the n^{th} harmonic content of i_C . N_h is the maximum harmonic order considered. $I_{C,n}$ can be readily calculated by applying Fast Fourier Transform to i_C given by (5.21). $P_{loss,C}$ so calculated forms the input to the heat transfer model of the capacitor described in (5.29) and (5.31). A more accurate T is then obtained. From the obtained T , the new ESR is determined using the following equation

$$ESR(T, f) = ESR(T_0, f) \times (\rho + \gamma \exp(-T / \zeta)) \quad (5.33)$$

In (5.33), ρ , γ and ζ are the coefficients determined from experimental measurements [234].

In this study, T is calculated in an iterative manner. The iterative process begins with the initial capacitor temperature set as T_0 , the ambient temperature T_{amb} . With the known operating state of the SPVG before the voltage disturbance, i_C can be determined from (5.21). The capacitor loss $P_{loss,C}$ at any given T , can be calculated using (5.32). From the new ESR , repeat the above calculation process to obtain $P_{loss,C}$ and thus the new T . The iteration stops when T converges.

Fig. 5.5 shows an example of the variation of ESR for new and used electrolytic capacitor versus frequency. Over a wide range of frequency, ESR is mostly constant. At low frequency, ESR increases as predicted by (5.27). However, the curve relating the ESR of used capacitor with frequency is not smooth, as shown in the figure. Similar result has also been reported in [239].

Since the duration of the disturbance is usually short compared to the thermal time constant of C_{DC} , it is assumed T is constant during the disturbance and is equal to that before the disturbance. Thus ESR under the disturbance condition can be set equal to the pre-disturbance ESR calculated using (5.33) at the pre-disturbance T . Following

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Fig. 5.5 Measured ESR of a new and used 5.4 mF capacitor versus frequency at 25 °C.

which $P_{loss,C}$ is calculated using (5.21) for the disturbance condition and then used in conjunction with the measured $P_{loss,inv}$ to yield P_{loss} for the evaluation of t_{max} using (5.9).

5.3.3. Impact of Capacitor Ageing

As the electrolytic capacitor in the SPVG is under continuous use, it tends to lose its electrolyte due to the heat generated in it. The electrolyte weight loss leads to a

Fig. 5.6 Capacitance (left) and ESR (right) evolution plots during accelerated ageing tests [236] © 2011 IEEE.

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decrease in its capacitance and its *ESR* increases. Fig. 5.6 shows the *ESR* and capacitance change during accelerated ageing tests. The capacitance experiences a small change at the beginning of operation and it is almost constant until near the end of its life when its capacitance decreases suddenly. Correspondingly, the *ESR* increases notably at the end of the capacitor life [236]. As a rule of thumb, capacitor is considered to be at the end of its life when it has lost about 40% of its electrolyte, and its capacitance value has decreased by 20%, compared to that when the unit is new. The corresponding *ESR* can be 2 - 3 times of its value at pristine condition [234, 236]. When this occurs, the load LVRT capability provided by the SPVG will be negatively impacted. Such ageing effect on C_{DC} shall be included in a new statistical approach described in the next section when evaluating the load LVRT capability of the power system shown in Fig 5.1.

5.4. Analysis of Load LVRT Probability

The statistical assessment of load LVRT capability of the power system shown in Fig. 5.1 can be carried out as follows. Assume P_L , P_{PV} and V_S are independent random variables. Firstly, voltage disturbances are usually treated as discrete events. Indeed, power quality surveys usually express the frequency of the disturbance occurrences in disjoint bins, expressed in terms of the voltage magnitudes and disturbance durations. See for example [41]. The voltage magnitude and duration could be treated as two random variables X and Y . From basic probability theory, one can define a set of events A for X and Y with interval widths of δ_x and δ_y as

$$A = \left\{ (x, y) \mid x \in \left[X_i - \frac{\delta_x}{2}, X_i + \frac{\delta_x}{2} \right] \& y \in \left[Y_j - \frac{\delta_y}{2}, Y_j + \frac{\delta_y}{2} \right] \right\} \quad (5.34)$$

The joint probability of X_i and X_j is then defined by

$$prob(X_i, Y_j) = \frac{N_A}{N_S} \quad (5.35)$$

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where N_A denotes the cardinal number of set A (i.e. number of elements in the set A) and N_S is the total number of events.

Based on the above, thus the voltage quality surveys allow the bivariate joint probability of voltage magnitude V_S and duration t_S , i.e. $prob(V_{S,k}, t_{S,n})$, to be determined using (5.35): $prob(V_{S,k}, t_{S,n})$ is the probability of voltage events with magnitude $V_{S,k}$ and duration $t_{S,n}$; and k and n are the respective indices. Finally, $prob(V_{S,k})$ can be calculated by summing the probability of all voltage disturbance events which have the magnitude of $V_{S,k}$ and of any duration, i.e.,

$$prob(V_{S,k}) = \sum_{t_S} prob(V_{S,k}, t_{S,n}) \quad (5.36)$$

In order to facilitate probabilistic analysis, the continuous random variables (RV) P_{PV} and P_L are to be discretized. Recall that the discrete probability of a random variable X can be expressed as

$$prob(X_j) = F_X\left(X_j + \frac{\sigma_x}{2}\right) - F_X\left(X_j - \frac{\sigma_x}{2}\right) \quad (5.37)$$

In (5.37), $prob(.)$ denotes the probability mass function of $(.)$ while $F_X(.)$ is the marginal cumulative density function (CDF) of $(.)$. X_j represents the discrete value of X over the interval range $[X_j - \sigma_x/2, X_j + \sigma_x/2]$, with σ_x being the width of the interval and j is an index. Hence using (5.37), the discrete probabilities of P_{PV} and P_L , i.e. $prob(P_{PV,l})$ and $prob(P_{L,m})$, can be calculated from the corresponding marginal CDF of P_{PV} and P_L respectively. l and m denote the corresponding indices of P_{PV} and P_L .

Consider a sag event k such that $V_S = V_{S,k}$. Suppose t_S is the duration of the voltage sag. Based on the analysis described in Chapter 3, the SPVG will be able to successfully provide load LVRT if the SPVG can inject active power of at least $P_{i,min,k,m}$ while $t_{S,n} \leq t_{max,k,l,m}$.

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Let $\mathfrak{R}_l$ denote a successful load low-voltage ride-through event for given $P_{PV,l}$. Based on the above observation, the probability of successful ride-through for given $P_{PV,l}$, $V_{S,k}$ and $P_{L,m}$ can be expressed as

$$\text{prob}(\mathfrak{R}_l | P_{L,m}, V_{S,k}) = \text{prob}(P_{PV,l}) \times \text{prob}(t_{\max,k,l,m} \geq t_{S,k} | V_{S,k}) \quad (5.38)$$

Consider the RHS of (5.38). Recall $t_{\max,k,l,m}$ is determined based on given $P_{PV,l}$, $P_{L,m}$ and $V_{S,k}$ using (5.9). Obviously if $t_{\max}$ is ∞ , then $\text{prob}(t_{\max,k,l,m} \geq t_{S,n} | V_{S,k}) = 1$. For the case of finite $t_{\max}$ however, $\text{prob}(t_{\max,k,l,m} \geq t_{S,n} | V_{S,k})$ shall depend on the number of sag events of the given magnitude (i.e. $V_{S,k}$) which have time durations less than or equal to $t_{\max}$. Thus, (5.38) shows that the probability of successful voltage ride-through is conditional on the occurrence of $V_{S,k}$. One notes that $\text{prob}(t_{\max,k,l,m} \geq t_{S,n} | V_{S,k})$ can be expressed as

$$\text{prob}(t_{\max,k,l,m} \geq t_{S,n} | V_{S,k}) = \sum_{t_{S,n} \leq t_{\max,k,l,m}} \frac{\text{prob}(V_{S,k}, t_{S,n})}{\text{prob}(V_{S,k})} \quad (5.39)$$

To guarantee load LVRT is successful for all the events in the $V_{S,k}$ bin, $P_{i,min}$ in this bin shall therefore be set equal to the corresponding $P_{i,min}$ for mitigating the most severe sag in this bin, i.e. $V_{S,k} - \delta_{Vs}/2$. δ_{Vs} denotes the voltage sag bin width used in the discretization procedure. Thus for other sag events within the interval $V_{S,k} - \delta_{Vs}/2 \leq V_S \leq V_{S,k} + \delta_{Vs}/2$, the SPVG shall have sufficient injected active power for restoring the load voltage.

Next consider the LHS of (5.38). By applying total probability law [240], one notes that

$$\text{prob}(\mathfrak{R}_l | P_{L,m}) = \sum_{k=1}^{N_{Vs}} \text{prob}(\mathfrak{R}_l | P_{L,m}, V_{S,k}) \times \text{prob}(V_{S,k}) \quad (5.40)$$

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where N_{V_S} is the total number of discretized V_S . It can be assumed all the ride-through events $\mathfrak{R}_l$ are disjointed, i.e. $\mathfrak{R}_i \cap \mathfrak{R}_j = 0$ for all i and j because no two events can occur at the same time. Thus the total successful of ride-through events for all possible P_{PV} , V_S and P_L is given by

$$RT = \bigcup_{l=1}^{N_{PV}} \mathfrak{R}_l \quad (5.41)$$

where N_{PV} is the total number of discretized P_{PV} . Whence, the probability of RT can be obtained by the summation of the probability of all $\mathfrak{R}_l$, i.e.

$$prob(RT) = \sum_{l=1}^{N_{PV}} prob(\mathfrak{R}_l) \quad (5.42)$$

Furthermore, based on probability theory, one notes that

$$prob(RT / X) = \sum_{l=1}^{N_{PV}} prob(\mathfrak{R}_l / X) \quad (5.43)$$

where X is a random variable. Replace X with $P_{L,m}$, thus the conditional probability of successful ride-through for the given load power $P_{L,m}$ can be written as

$$prob(RT / P_{L,m}) = \sum_{l=1}^{N_{PV}} prob(\mathfrak{R}_l / P_{L,m}) \quad (5.44)$$

Finally, the probability of successful ride-through can be determined by applying total probability law at the various P_L for $prob(RT|P_{L,m})$, i.e.

$$prob(RT) = \sum_{m=1}^{N_{PL}} prob(RT / P_{L,m}) \times prob(P_{L,m}) \quad (5.45)$$

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where N_{PL} is the total number of possible discretized P_L . $prob(P_{L,m})$ is the probability of load at the specific level and it can be obtained from recorded empirical load data.

Equation (5.45) provides the means to evaluate the effectiveness of the SPVG in enhancing load LVRT and can be applied to C_{DC} of different capacity. Application of this assessment method shall be illustrated using the numerical examples in Section 5.6. Indeed, by weighting the benefit of achieving such enhanced voltage quality against the cost of the capacitor energy storage element, it is possible to arrive at a design which provides a judicious balance between the two conflicting factors. This would be a fruitful area for more investigation, as shall be pursued in Chapter 6.

5.5. Experimental Validation of Load LVRT Capability

In an attempt to validate the accuracy of the developed model to determine the maximum duration of load LVRT (t_{max}), the experimental prototype of the SPVG has been used and experimental measurements carried out in the laboratory. The SPVG consists of a full-bridge bidirectional inverter and a boost converter, designed with the parameters shown in Table A.2. The switching frequency of the inverter, which is based on SPWM technique, is set at 2 kHz while that of the boost converter is 20 kHz. The inverter control scheme is similar to that explained in Chapter 3. A new 5.4 mF capacitor of suitable voltage rating was available in the author's laboratory. Thus in order to facilitate comparison with the theoretical results obtained later, this capacitor was selected for use in the prototype. The impedance of the new capacitor was measured by an impedance analyzer and its parameters were determined and as shown in Table A.2.

The experimental setup is shown in Fig 5.7. Up to 6 PV modules of the type GL130 were connected to the SPVG. The SPVG was inter-connected to the grid without the series transformer as the output voltage level of the SPVG matches satisfactorily with that of the laboratory supply system.

Various tests have been carried to evaluate the load LVRT capability of the SPVG. Fig. 5.8 shows a sample of the test results. It pertains to the recorded V_S , V_L , V_i and V_{DC} when V_S was reduced to 10% for a duration of 500 ms. At the time of the test,

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Fig. 5.7 Experimental set-up of the SPVG prototype.

$P_{PV} \approx 120$ W. As can be seen from the figure, some 130 ms from the initiation of the voltage sag, V_L began to decrease as by then, V_{DC} was unable to maintain its level. Even though the SPVG did restore V_{DC} and V_L to their nominal values when the sag was over, this was considered a case of un-successful load LVRT. Indeed, based on the calculation using (5.9), for voltage sag of this severity, the maximum ride-through duration for the designed SPVG is 141 msec. Hence, the experimental result is consistent with the theoretical prediction.

Fig. 5.8 Experimental results obtained from the SPVG prototype: 90% 500 msec voltage sag when $P_{PV} \approx 120$ W.

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Since the varying solar irradiance will induce the output power of the PV panels to vary, an Agilent solar array simulator was later incorporated to the laboratory test set-up. This was with the view to simulate the steady state and stable irradiance conditions and was an attempt to obtain a more accurate determination of t_{max} . Fig. 5.9(a) compares the theoretical calculated t_{max} based on (5.9) with those obtained from the various experiments carried out on the SPVG prototype over a wide-range of P_{PV} .

(a)

(b)

Fig. 5.9 Comparison between the theoretical and experimentally measured t_{max} for various sag magnitude and P_{PV} . (a) $Z_s = 0$, (b) $Z_s = 0.027$ p.u.

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It can be seen in Fig. 5.9(a) that the two sets of results agree amicably well. The small differences can be attributed to the uncertainty in the system parameters used in the theoretical calculation, such as the source impedance and power losses. One can see that by increasing P_{PV} , the ability of the SPVG in load LVRT improves. For example, for $P_{PV} \approx 175$ W, $t_{max} = 1.58$ sec for $V_S = 0.3$ p.u. whereas under no-sun condition (i.e. $P_{PV}=0$), t_{max} has been reduced to 145 msec.

t_{max} calculated with Z_S included in evaluating P_{imin} is shown in Fig. 5.9(b). There are differences between the results of Fig. 5.9(a) and Fig. 5.9(b) but the differences are very small.

5.6. Numerical Examples

Numerical examples shall now be used to illustrate the proposed statistical approach. SPVG parametric values used in this study are identical with those in the SPVG laboratory prototype used in the tests. The pertinent parameters have been presented in Table A.2 which includes the specifications of the PV modules.

5.6.1. Preliminary Data Preparation

Firstly, the insolation level (I_{ns}) recorded at the author's campus in 2009-2010 was analyzed. Then based on the analytical solution presented in [201], maximum harnessable P_{PV} was calculated for the recorded I_{ns} . CDF of P_{PV} was obtained. Fig. 5.10 shows the probability distribution and CDF of P_{PV} obtained for one PV module.

Next, suppose the load P_L behaves in a similar manner as that described in [196]. The one year hourly recorded load data in 2010 has been analyzed and the empirical PDF and CDF of P_L were determined. Then the discrete probability of the normalized P_L is calculated and shown in Fig. 5.11, on 323 VA base. Finally, the voltage sag statistics was assumed to be that shown in [41]. This statistics were obtained from a power quality survey. The joint probability $prob(V_S, t_S)$ which relates voltage sag magnitude and duration is as shown in Fig. 5.12. As shown in the figure, most of the events have duration less than 1 sec and magnitude larger than 0.5 p.u. For example, $prob(V_S = 0.85, t_S < 120$ msec), i.e. $0.8 < V_S < 0.9$, is equal to 0.3954.

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$Prob(V_S = 0.85)$ is the summation of all sag events with magnitude of $0.8 < V_S < 0.9$ and different duration. From the figure, therefore,

$$prob(V_S = 0.85) = 0.3954 + 0.0931 + 0.0444 + 0.0201 + 0.0258 + 0.0072 + 0.0057 + 0.0014 = 0.5931$$

A similar procedure allows the summated probability of other sag events to be determined.

Fig. 5.10 Cumulative distribution function and discrete probability of P_{PV} .

Fig. 5.11 Probability of load power, P_L .

Fig. 5.12 Probability of voltage sag plotted at various V_S and sag duration t_S .

5.6.2. Probability of Voltage Sag Ride-through

5.6.2.1. SPVG without significant energy storage capacity

Initially, assume that the SPVG does not have any significant energy storage capacity in the form of C_{DC} . For instance, a relatively small C_{DC} of 0.54 mF has been assumed installed in the DC-link for power decoupling and ripple reduction of V_{DC} in the present numerical example. Using (5.44) derived in Section 5.4, the probability of successful voltage sag ride-through was then determined for different P_L . The results are shown in Fig. 5.13. As expected, it shows the probability of successful voltage sag ride-through decreases as P_L increases. For example, at load level of 1 p.u. 0.8 lagging power factor, the probability of voltage sag ride-through is only about 60% of that at 0.1 p.u load.

5.6.2.2. SPVG with C_{DC} Rated at 5.4 mF

Consistent with the SPVG prototype in which a 5.4 mF capacitor has been incorporated, a new 5.4 mF capacitor has been assumed to be the energy storage

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element in the SPVG. With this new capacitor in the SPVG, the corresponding probability function of successful load LVRT at various values of P_L was evaluated and the results shown in Fig. 5.13. The capacitor has indeed greatly improved the probability of load LVRT, although this voltage quality enhancement capability does deteriorate with the increase in load level.

The study has also considered the case of the capacitor which is at the end of its life. Compared to the new C_{DC} , the ESR was assumed to be three times larger and its capacitance has decreased by 20%. The probability function of successful load LVRT has been recalculated. Furthermore, cases of with/without the inverter and C_{DC} internal losses in the SPVG have been studied. All these results are summarized in Fig. 5.13. As expected, the ideal lossless case is shown to indicate higher probability of load LVRT, as compared to the cases in which losses have been included. The losses increase with load and in addition, as heavier loads require larger amount of stored energy for successful load LVRT, the capability of the SPVG to support load LVRT decreases.

Closer examination of Fig. 5.13 shows that the curves describing the probability of load LVRT versus P_L are not perfectly smooth, especially for a SPVG incorporated with a lower capacitance ESS. The reason for this is because discrete voltage sag intervals (including both sag magnitude and duration) and discrete load quantities have been used in the study to construct the curves. In the study, to determine the load LVRT ability for a given P_L , the probability is calculated for all voltage sags intervals using (5.38)-(5.45). Based on the study results and the voltage sag statistics, one can then determine the probability of successful load LVRT at the P_L level. The process is repeated to identify load LVRT at other load conditions. As the number of sag events is discretized, therefore, the probability of successful load LVRT for given P_L will appear in less than a smooth manner.

Using (5.45), the probability of the load LVRT afforded by the SPVG using the new as well as the end-of-life 5.4mF capacitors and the lossless SPVG has been calculated. The results are depicted in Fig. 5.14. For the case of the 5.4 mF lossless capacitor, the predicted load LVRT probability is about 0.956 as compared to 0.937

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Fig. 5.13 Probability of load LVRT plotted against P_L for C_{DC} of different energy storage capacity.

and 0.918 for the new and end-of-life capacitors respectively. The probability reduces sharply to 0.641 for the case of 0.54 mF C_{DC} . Another interesting observation is that as the capacitance of the capacitor increases beyond (say) 7 mF, the probability of successful load LVRT starts to taper off. This is because P_{loss} becomes increasingly less significant relative to the stored energy capacity of the capacitor as the capacitance increases: P_{loss} has less of an impact on the load LVRT capability of the SPVG.

A range of new and end-of-life capacitors of various rated capacitances have also been considered in this study. The total LVRT probability of the different C_{DC} has been summarized in Fig. 5.14 as well. As can be seen from the figure, the ideal lossless SPVG model consistently predicts higher probability of load LVRT and cannot be relied on to predict the actual performance of the SPVG. On the other hand, the more realistic SPVG model proposed in this investigation provides more dependable information for the design of the SPVG. For instance, if the design objective is to achieve a 0.9 probability of load LVRT, then Fig. 5.14 shows that a C_{DC} of 4.35 mF would be sufficient. This is because even when this capacitor is at the end of its life, it can still provide the 0.9 probability of load LVRT.

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Fig. 5.14 Probability of load LVRT of ideal lossless, new and end-of-life C_{DC} of various capacitances.

Now the design based on the worst-case scenario can be compared with that using the statistical approach. Assume the worst-case for the condition of maximum load ($P_L = 1$ p.u.), no sun ($P_{PV} = 0$) and the most severe sag of $V_S = 0.1$ p.u. and duration of 1 sec. Based on the network example shown in Chapter 5 and (5.9), it can be readily shown that this will require a capacitor ESS of comparatively large capacitance C_{DC} of 93.2 mF. With this capacitance and based on the statistical data of sag events given in [41] for $V_S > 0.1$ and $t_s < 1$ s, the SPVG is able to mitigate 96.7% of the sag events.

In probabilistic approach, suppose one intends to achieve load LVRT for 96.7% of the sag events. The SPVG will require a C_{DC} of 11.8 mF. Obviously the probabilistic approach has resulted in the need of much smaller C_{DC} than that based on the deterministic approach and conventional deterministic can lead to the over design of the ESS.

5.7. Conclusions

Within the SPVG, the energy stored in the DC-link capacitor is to be utilized to provide any shortfall in the injected power required to maintain the load voltage

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constant. However, internal power losses in the capacitor can lead to an increase in ESR and a decrease in the capacitance of the capacitor. These changes can reduce the ability of the SPVG to maintain voltage quality. These factors were included in the analysis.

Due to the random behavior of the solar insolation, voltage sag occurrence as well as load variation, a new statistical approach was adopted to evaluate the effectiveness of the proposed voltage quality enhancement scheme. A method to evaluate the probability of successful load low voltage ride-through was developed so that the ability of the SPVG in restoring the load voltage could be readily assessed. The proposed approach also allows the effectiveness of C_{DC} in influencing the load LVRT capability of the SPVG to be quantified. It is observed that by the appropriate selection of the C_{DC} capacity, the probability of load LVRT can be significantly improved. The accuracy of the predicted maximum sag duration (t_{max}) under which successful load LVRT can be achieved was validated through comparison with experimental results obtained from tests carried out on a prototype SPVG.

In this chapter, it has been assumed that the load and photovoltaic power are independent random variables. This assumption may not be accurate. Furthermore extension of the proposed approach to other types of renewable sources could be fruitful area for future work. Thus in the next chapter, a general probabilistic method is presented which can be applied to any stochastic power generation. The possible correlation between solar and load is also examined in greater detail.

Chapter 6. A Generalized Statistical Approach to Evaluate Load Low-voltage Ride-through Capability Provided by Distributed Renewable Generator

6.1. Introduction

Capability of a distributed renewable generator (DRG) to support grid during faults shall depend on several factors, such as the severity of the disturbance, the level of the renewable power and load demand at the instance of the disturbance. These are time-varying and/or random variables. Thus, a deterministic approach to analyze the contribution made by the DRG toward the voltage quality enhancement is inappropriate as it could lead to misleading conclusions. Thus unlike Chapter 3 and previous works [13-17, 23-25, 31], this chapter treats the renewable power, load and voltage disturbances as random variables when assessing the capability of a DRG in providing voltage quality improvement. As studied in Chapter 5, load demand and renewable source are considered independent but in this chapter, the stochastic dependency between the renewable power and load demand is specifically included in the analysis. Furthermore in this chapter, the impact of energy storage system (ESS) and stochastic behavior of load, renewable power and voltage disturbance on LVRT capability of DRG is studied in a form regardless of the type renewable source and connection of DRG to grid. It is shown that the probability of successful load LVRT is dependent of the rated power/energy capacities of the DRG, and the probability can be further increased through supportive actions of the ESS. The stochastic approach allows the optimal capacities of the DRG and the ESS to be determined, by weighting the expected economic benefits obtained from the harnessed energy and load LVRT against the cost of the DRG-ESS.

The chapter is thus structured as follows: Section 6.2 shall provide details of the statistical analysis and approach to assess the ability of the DRG in providing voltage

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quality enhancement. The approach is then applied to a series-connected DRG-ESS in Section 6.3 to show how the capacities of the DRG-ESS impact on the probability of successful load LVRT. A statistical approach to optimize DRG-ESS capacity is proposed in Section 6.4. Numerical examples are included in Section 6.5 to illustrate the proposed statistical approach.

6.2. Probabilistic Analysis of Load LVRT

Fig. 6.1 shows a generic distribution network interconnected to an upstream grid system. The DRG-ESS is shown shunt-connected, although series-connected DRG-ESS may also exist. A series-connected DRG-ESS would be effective in improving voltage quality in a strong grid system, as shall be shown in the next section. The loads in the distribution system could be partially met by the generated power P_g from the DRG. As the focus of this study is on the provision of LVRT for sensitive load in the system due to voltage disturbance, the figure highlights the voltage and power demand of such a sensitive load by specifically denoting them as $\bar{V}_L$ and P_L respectively. The voltage disturbance shall be treated as a decrease in the magnitude of $\bar{V}_s$, i.e. a sag event. In general, sensitive load has certain built-in LVRT capability although this capability is often inadequate [206, 207]. The DRG could, accordingly, adjust its active and reactive output powers to assist the load in riding through the sag. Unfortunately the DRG is an intermittent power source and thus, the extent by which the DRG could contribute toward successful load LVRT is uncertain. The installed ESS can act as an alternative power source during the sag but in practice, the ESS has finite energy capacity. For a given voltage sag event, let t_{max} denote the maximum duration the combined DRG-ESS is capable of maintaining V_s to an acceptable level. Thus load LVRT is successful if the duration t_s of the voltage sag is equal to or less than t_{max} . Clearly t_{max} depends on the severity of the sag, and the levels of P_g and P_L at the precise moment of the sag. One recognizes sag events, P_g and P_L are random variables (RV). Thus the choice of a probabilistic approach is appropriate when assessing the load LVRT support afforded by the DRG-ESS. An explanation on how to treat the statistical data of P_g , P_L and voltage sag is called for, as follows.

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Fig. 6.1 A generic distribution network containing DRG, ESS and sensitive load.

6.2.1. Treatment of the Statistical Data of P_g , P_L and Voltage Disturbances

Consider firstly the power generation from the DRG. The probability of P_g being at a particular level can be determined based on the historical data of P_g recorded at the renewable site. For example, from the recorded wind speed data and known turbine power-wind speed curve, the probability distribution of P_g can be determined in a manner similar to that described in [241] or as described in Section 5.3. Similarly, if P_g is from a photovoltaic source, based on the recorded solar insolation level, technique described in Chapter 2 and using MPP analytical solution [201], the probability distribution of P_g from the PV generator can also be readily obtained. Furthermore, the statistical characteristic of P_g from the wind or PV DRG can be expressed in terms of its CDF.

On the demand side, the long-term recorded data of P_L can be readily extracted from utility and/or customer databases. The CDF of P_L could be similarly constructed.

P_g and P_L are continuous RV and they have to be discretized to facilitate analysis. Hence, the discrete probabilities of P_g and P_L , i.e. $prob(P_{g,l})$ and $prob(P_{L,m})$, can be calculated from the corresponding marginal CDF of P_g and P_L respectively based on the discretization method explained in Section 5.4. l and m denote the corresponding

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indices of P_g and P_L .

$prob(V_{S,k}, t_{S,n})$ and $prob(V_{S,k})$ can be readily calculated using voltage quality surveys data and the method described in Chapter 5 where $V_{S,k}$ and $t_{S,n}$ denote discretized voltage sag magnitude and sag duration respectively. k and n are the respective indices.

6.2.2. Probabilistic Analysis of Load LVRT

Consider a sag event k in which $V_S = V_{S,k}$ and of duration t_S . Let $\mathfrak{R}_l$ denote the set of successful load LVRT events for a given $P_{g,l}$. Therefore $\mathfrak{R}_l$ includes all the successful load ride-through events for all possible P_L when $V_S = V_{S,k}$, $P_g = P_{g,l}$ and for which the durations of the sags are less than the maximum duration t_{max} the DRG-ESS is capable of supporting the load LVRT. Among the $\mathfrak{R}_l$ set of events, if one were to examine only those cases at a specific load level of $P_{L,m}$, then t_{max} for which successful ride-through is possible shall be denoted as $t_{max,k,l,m}$. The subscript “ k,l,m ” in $t_{max,k,l,m}$ signifies that the value of $t_{max,k,l,m}$ depends on the precise levels of $V_{S,k}$, $P_{g,l}$ and $P_{L,m}$. This load LVRT probability can be expressed as

$$prob(\mathfrak{R}_l / P_{L,m}, V_{S,k}) = prob(P_{g,l}, t_S \leq t_{max,k,l,m} / P_{L,m}, V_{S,k}) \quad (6.1)$$

It is reasonable to assume that the successful load LVRT event set $\mathfrak{R}_i$ when the DRG output power $P_g = P_{g,i}$ and the set $\mathfrak{R}_j$ when $P_g = P_{g,j}$ are disjointed, i.e. the two sets of events cannot occur concurrently and therefore, $\mathfrak{R}_i \cap \mathfrak{R}_j = 0$. Thus the set RT which includes all successful ride-through events for all possible P_g , V_S and P_L is given by the union of all $\mathfrak{R}_l$:

$$RT = \bigcup_{l=1}^{N_g} \mathfrak{R}_l \quad (6.2)$$

where N_g is the total number of discretized P_g .

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Also, the conditional probability RT for a given random variable X is obtained by the summation of the conditional probability of $\mathfrak{R}_l$ of all X , i.e.

$$prob(RT / X) = \sum_{l=1}^{N_g} prob(\mathfrak{R}_l / X) \quad (6.3)$$

For the problem in hand, X is either $P_{L,m}$ or $V_{S,k}$. Therefore, the conditional probability of successful load LVRT for given $V_{S,k}$ and $P_{L,m}$ can be determined using (6.1) and the definition of multivariable conditional probability [240] to yield

$$prob(\mathfrak{R}_l / P_{L,m}, V_{S,k}) = \frac{prob(P_{g,l}, P_{L,m}, V_{S,k}, t_S \leq t_{max,k,l,m})}{prob(P_{L,m}, V_{S,k})} \quad (6.4)$$

The numerator of the RHS term of (6.4) can be determined by the summation of all possible sag events which have durations less than or equal to $t_{max,k,l,m}$ for the given $V_{S,k}$ and $P_{L,m}$, i.e.,

$$prob(\mathfrak{R}_l / P_{L,m}, V_{S,k}) = \sum_{t_S \leq t_{max,k,l,m}} \frac{prob(P_{g,l}, P_{L,m}, V_{S,k}, t_S)}{prob(P_{L,m}, V_{S,k})} \quad (6.5)$$

Next, it would be reasonable to assume that the upstream voltage sags are uncorrelated events to the DRG generation P_g and load P_L . On the other hand, P_g and P_L themselves could be correlated, a possibility which will be examined more closely in the next section. So based on this assumption, the probability of successful load LVRT for given $P_{L,m}$ and $V_{S,k}$ can be evaluated as follows. From (6.5), one obtains

$$prob(\mathfrak{R}_l / P_{L,m}, V_{S,k}) = \sum_{t_S \leq t_{max,k,l,m}} \left[\frac{prob(P_{g,l}, P_{L,m})}{prob(P_{L,m})} \times \frac{prob(V_{S,k}, t_S)}{prob(V_{S,k})} \right] \quad (6.6)$$

Then based on the definition of conditional probability, the first term on the RHS of

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(6.6) can be expressed as

$$\frac{\text{prob}(P_{g,l}, P_{L,m})}{\text{prob}(P_{L,m})} = \text{prob}(P_{g,l} | P_{L,m}) \quad (6.7)$$

In the 2nd term on the RHS of (6.6), $\text{prob}(V_{S,k}, t_s)$ can be obtained from utility voltage quality survey as alluded to in Section 6.2.1, whereas $\text{prob}(V_{S,k})$ can be calculated using (5.36). Therefore, substitute (6.7) into (6.6) and apply the total probability theorem for all possible V_S , the conditional probability of load LVRT for a given $P_{L,m}$ can be calculated:

$$\text{prob}(\mathfrak{R}_l | P_{L,m}) = \sum_{k=1}^{N_{V_S}} \left[\text{prob}(P_{g,l} | P_{L,m}) \times \sum_{t_s \leq t_{\max,k,l,m}} \text{prob}(V_{S,k}, t_s) \right] \quad (6.8)$$

where N_{V_S} is the total number of discretized V_S .

Substitute (6.8) into (6.3), the conditional probability of total successful load LVRT for the given $P_{L,m}$ is the summation of all conditional probabilities of disjointed events $\mathfrak{R}_l$, i.e.,

$$\text{prob}(RT | P_{L,m}) = \sum_{l=1}^{N_g} \sum_{k=1}^{N_{V_S}} \left[\text{prob}(P_{g,l} | P_{L,m}) \times \sum_{t_s \leq t_{\max,k,l,m}} \text{prob}(V_{S,k}, t_s) \right] \quad (6.9)$$

In similar manner, one can express the conditional probability of load LVRT for a given $V_{S,k}$ for all possible P_L as

$$\text{prob}(\mathfrak{R}_l | V_{S,k}) = \sum_{m=1}^{N_{P_L}} \left[\text{prob}(P_{g,l}, P_{L,m}) \times \sum_{t_s \leq t_{\max,k,l,m}} \frac{\text{prob}(V_{S,k}, t_s)}{\text{prob}(V_{S,k})} \right] \quad (6.10)$$

Whence using (6.3), the conditional probability of total successful load LVRT for the

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given $V_{S,k}$ can be determined:

$$prob(RT | V_{S,k}) = \sum_{l=1}^{N_g} \sum_{m=1}^{N_{PL}} \left[prob(P_{g,l}, P_{L,m}) \times \sum_{t_s \leq t_{\max,k,l,m}} \frac{prob(V_{S,k}, t_s)}{prob(V_{S,k})} \right] \quad (6.11)$$

N_{PL} is the total number of possible discretized P_L .

Finally, the probability of successful ride-through can be determined using (6.9) by considering all P_L , i.e.

$$prob(RT) = \sum_{m=1}^{N_{PL}} prob(RT | P_{L,m}) \times prob(P_{L,m}) \quad (6.12)$$

The term $prob(P_{L,m})$ on the RHS of (6.12) can be determined from utility long-term load data measurement.

Thus, using (6.9) and (6.12), it is possible to statistically evaluate the effectiveness of the DRG-ESS in providing load LVRT. In order to do so however, it does require the probability function $prob(P_g, P_L)$ in (6.9) be known. This can be done by constructing a model to describe the dependency between P_g as P_L , as shown in the next subsection.

6.2.3. Modeling the Stochastic Dependency Between P_g and P_L

In power system analysis, joint normal distribution is often used to model the dependency between random variables (RV) which are normally distributed. There are well-established methods to calculate the joint distribution. However, in cases where the RV are not normally distributed, alternative method has to be found. This investigation proposes to use copulas in an attempt to model the stochastic dependency between P_g and P_L . In fact, the approach is sufficiently general and is applicable when determining the dependency between RV of any kind of probability distributions. This section will only briefly describe the analytical steps involved in

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the use of copulas, as interested readers can find more details on the subject matter in [198, 242]. The use of copulas in power system studies is also not new. For example, the authors of [243] have adopted the technique to model the dependency between transformer load and ambient temperature. They have shown that a more accurate transformer loss of life inference can be obtained. The present investigation also adopts the technique, with the view to model the function $prob(P_g, P_L)$.

Firstly, apply Sklar theorem [242] to obtain the joint distribution function or joint cumulative distribution functions $F_{P_g P_L}(P_g, P_L)$ of the random variables P_g and P_L which have the marginal distributions $F_{P_g}(P_g)$ and $F_{P_L}(P_L)$. It can be established that there exists a function C_{UV} such that

$$F_{P_g P_L}(P_g, P_L) = C_{UV}(F_{P_g}(P_g), F_{P_L}(P_L)) \quad (6.13)$$

$C_{UV}(\cdot)$ is called a copula function. Denote $F_{P_g}(P_g) = u$ and $F_{P_L}(P_L) = v$ and if F_{P_g} and F_{P_L} are invertible, one can write

$$C_{UV}(u, v) = F_{P_g P_L}(F_{P_g}^{-1}(u), F_{P_L}^{-1}(v)) \quad (6.14)$$

Equation (6.13) can be used to find the joint distribution of P_g and P_L . The copula method is a technique to develop a new set of the RV which has similar stochastic behavior as P_g and P_L and the new RV will be correlated at specific level. To do so, the first step is to transfer P_g and P_L into their respective rank domains using a technique called CDF transformation [198, 242]. The transferred P_g and P_L retain the dependency structure of the original P_g and P_L . Denote P_g and P_L in the rank domain as P_g^* and P_L^* respectively. Then, the rank correlation ρ_r between P_g and P_L is evaluated as follows. ρ_r is defined as linear correlation between ranks of P_g and P_L , and is defined as

$$\rho_r(P_g, P_L) = \rho(F_{P_g}(P_g), F_{P_L}(P_L)) = \rho(P_g^*, P_L^*) \quad (6.15)$$

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ρ denotes linear correlation between two random variable. ρ_r measures the degree to which large and small values of P_g^* are associated with large and small values of P_L^* . The obtained rank correlation can then be used as input to one of several commonly-used copula functions. The copula function generates another set of stochastic variables in the rank domain, using the procedure described in [197, 244]. These variables are in turn transformed back to their original domain through inverse CDF transform, again by following the technique explained in [198],[243]. This procedure can be repeated for the various copula functions. The copula which models most accurately the stochastic characteristics of P_g and P_L can be found using the Kolmogorov-Smirnov (KS) goodness-of-fit test, by comparing the original data distribution and that obtained from the copula function [245]. The most promising copula function is then selected to model of stochastic dependence between P_g and P_L using (6.13).

With known $F_{PgPL}(P_g, P_L)$, the joint probability of P_g and P_L can be readily calculated by recognizing that,

$$\begin{aligned} prob(P_{g,l}, P_{L,m}) = & F_{PgPL}\left(P_{g,l} + \frac{\sigma_g}{2}, P_{L,m} + \frac{\sigma_L}{2}\right) + F_{PgPL}\left(P_{g,l} - \frac{\sigma_g}{2}, P_{L,m} - \frac{\sigma_L}{2}\right) \\ & - F_{PgPL}\left(P_{g,l} + \frac{\sigma_g}{2}, P_{L,m} - \frac{\sigma_L}{2}\right) - F_{PgPL}\left(P_{g,l} - \frac{\sigma_g}{2}, P_{L,m} + \frac{\sigma_L}{2}\right) \end{aligned} \quad (6.16)$$

where σ_g and σ_L denote the width of the discretization intervals for P_g and P_L respectively. The application of the above procedure in calculating $prob(P_g, P_L)$ shall be illustrated in Section 6.5.

With $prob(P_g, P_L)$ so determined, therefore, one is able to statistically evaluate the effectiveness of the DRG-ESS in providing load LVRT using (6.9) and (6.12). In the next section, a series-connected DRG-ESS is used to demonstrate how the judicious use of the DRG-ESS can achieve the desired load LVRT.

6.3. A Series-Connected Distributed Renewable Generator with Capacitor ESS

In general and as explained in Chapters 2 and 3, a series-connected power quality conditioner is more effective than shunt-connected conditioners in providing load LVRT when it is connected to a tightly-coupled upstream grid system [56],[116]. The Singapore grid is such a network. Hence, a series-connected DRG-ESS similar to that described in Chapter 3 shall be utilized in this section to illustrate how the capacity of the DRG-ESS can be determined through balancing the cost of the device against the expected economic benefits of the renewable energy harness and load LVRT.

6.3.1. Steady-state Operation of the DRG During Voltage Sag

Fig. 6.2 shows the schematic diagram of the series-connected DRG considered in this Section. The DRG is shown connected to the PV and/or wind renewable sources and is augmented by the capacitor energy storage element C_{DC} . The upstream source open-circuit voltage is denoted as $\bar{E}_S$ and the supply voltage to the load is $\bar{V}_S$. Z_S denotes the equivalent source impedance. In a tightly-coupled grid, Z_S is negligible in comparison with the sensitive load impedance. The upstream source is assumed to be

Fig. 6.2 Schematic of the series-connected distributed generator in the grid system.

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a stiff grid system such that $\bar{V}_S \approx \bar{E}_S$ as Z_S is negligible in comparison with the sensitive load impedance. The load draws a complex power $P_L + jQ_L$, and the DRG is to regulate its output power $P_i + jQ_i$ and $\bar{V}_i$ such that the load voltage magnitude V_L remains constant in the face of variations in $\bar{V}_S$. The operating principle and control of the DRG-ESS can be found in Chapter 3.

For a given voltage sag $E_S (= V_S)$, the analysis in Chapter 3 shows that for the sensitive load to achieve successful LVRT, the DRG-ESS injected power P_i must satisfy the inequality equation

$$P_L - E_S I_L + R_S I_L^2 \leq P_i \leq P_L + E_S I_L + R_S I_L^2 \quad (6.17)$$

Inequality (6.17) shows that for the successful load LVRT, P_i has to be at least equal to the minimum value $P_{i,min} = P_L - E_S \times I_L + R_S \times (I_L)^2$. $P_{i,min}$ can be readily determined from the known pre-sag steady-state values of P_L , S_L and V_L . During instances of low solar insolation or wind speed, however, P_g can be lower than $P_{i,min}$. In which case, the DRG may not be able to provide enough injected power for load LVRT. Hence, the energy stored in the capacitor C_{DC} shall be extracted to provide the shortfall $P_{i,min} - P_g$. However, during the discharging of the capacitor, V_{DC} should not fall below a certain pre-set level $V_{DC,min}$ to avoid the over-modulation of the PWM inverter.

As shown in Chapter 3, with known P_i , P_L , Q_L , E_S and Z_S , the required injected reactive power Q_i is given by

$$Q_i = Q_L - E_S I_L \sqrt{1 - \left(\frac{(P_L - P_i)}{I_L E_S} + \frac{R_S I_L}{E_S} \right)^2} + X_S I_L^2 \quad (6.18)$$

Chapter 3 shows that the control of the injected power is such that $P_i + j Q_i$ is constrained to within the power rating of the PWM inverter. Hence, there is no danger the DRG-ESS would be forced to disconnect from the grid due to the overloading of the inverter. Another factor not considered in Chapter 3 but which can

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affect load LVRT is the losses in the power conversion stages of the DRG-ESS. Denote the steady-state power losses in the inverter circuit as P_{loss} , thus

$$P_g = P_i + P_{loss} \quad (6.19)$$

P_{loss} includes switching and conduction losses in the inverter. These losses have been considered in Chapter 5. Accurate evaluation of P_{loss} requires complex calculation. For constant DC-link voltage and switching frequency, the switching loss is approximately proportional to the load current. Also, as the DRG-ESS is series-connected to the load, I_i is equaled to the load current I_L . The conduction loss is therefore proportional to I_i^2 or I_L^2 . Thus, for a given load, P_{loss} is mostly affected by the load level. Thus one may assume that P_{loss} is proportional to the load. This is shown to be a reasonable assumption, based on the test results obtained from the DRG-ESS prototype to be described later.

6.3.2. Determination of $t_{max,k,l,m}$ and Experimental Validation

In Section 6.2.2, it has been explained that the probability of load LVRT also depends on the duration of the voltage sag. The duration of an upstream voltage sag event is usually so short that there should not be appreciable variations of the renewable power P_g during the sag. Hence, one can assume P_g is constant during the sag event. Following the approach of Section 6.2, P_g , V_S and P_L are treated as discrete RV. At the instance when a voltage sag occurs, if $P_{g,l} > P_{i,min,k,m} + P_{loss}$, then the harnessed P_g is sufficient to support the load for LVRT. Thus the DRG can continuously maintain V_L for duration considerably longer than that usually encountered in voltage sag. However, if $P_{g,l} < P_{i,min,k,m} + P_{loss}$, the DRG shall draw energy from the capacitor C_{DC} to provide the short-fall $P_{i,min,k,m} + P_{loss} - P_{g,l}$. However, it is necessary to maintain the voltage across C_{DC} to above $V_{DC,min}$. Recall again from Chapter 5, by taking into account the discharged energy from C_{DC} , the maximum duration $t_{max,k,l,m}$ the capacitor can sustain the load LVRT is

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$$t_{\max,k,l,m} = \begin{cases} \infty & \text{if } P_{g,l} \geq P_{i,\min,k,m} + P_{\text{loss}} \\ \frac{C_{DC}(V_{DCn}^2 - V_{DC\min,k}^2)}{2(P_{i,\min,k,m} + P_{\text{loss}} - P_{g,l})} & \text{if } P_{g,l} < P_{i,\min,k,m} + P_{\text{loss}} \end{cases} \quad (6.20)$$

$t_{\max,k,l,m}$ is clearly a function of $P_{g,l}$, $V_{S,k}$ and $P_{L,m}$. This is a specific case demonstrating the general observation made in Section 6.2.1 on the maximum sag duration a DRG-ESS can support load LVRT.

The series-connected DRG prototype described in Chapters 3 and 5 is again used to verify the performance of the DRG-ESS shown in Fig. 6.2. The DRG consists of a full-bridge single phase bidirectional inverter and a boost converter, the details of which are given in Chapter 3. The nominal load voltage is 100V. The load is rated 323 VA at 0.8 lagging power factor. The renewable source consists of 6 PV modules. At the insolation level of 1000 w/m², each module can output 3.11 A at 14.5 V or 45W. $V_{DC,n}$ is 160V at rated PV output. Inverter loss P_{loss} measured at various P_g is about 25W when $S_L = 1$ p.u. P_{loss} decreases to some 20W when S_L reduces to 0.8 p.u. A 5.4 mF capacitor C_{DC} is used as the ESS. A dSPACE (DS1103) platform with MATLAB/Simulink in Real-Time Interface (RTI) is utilized to implement the control system.

Various tests have been carried out to evaluate the load LVRT capability afforded by the DRG-ESS but due to space constraint, only a sample of the experimental results for a successful load LVRT is presented in Fig. 6.3(a). The recorded V_S , V_L , V_i and V_{DC} when V_S was reduced to 40% for a duration t_s of 500 ms are shown in Fig 6.3(a). At the given system condition and sag severity, using (6.20), $t_{\max,k,l,m}$ is calculated to be approximately 1.22 sec. Since $t_s < t_{\max}$, load LVRT is expected to be successful, as borne out in Fig. 6.3(a).

Successful load LVRT for a 50% sag is demonstrated in Fig. 6.3(b). Since in this instance, $P_g > P_{i,\min} + P_{\text{loss}}$, based on (6.20), it is predicted that the SPVG shall be able to maintain the load voltage indefinitely. Indeed, Fig. 6.3(b) confirms this prediction: it shows V_{DC} remains constant while there is hardly any discernible

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Fig. 6.3 Experimental results of DRG-ESS: (a) under a 60% voltage sag and when $P_g \approx 120$ W showing supply, load, injected and DC-link voltages; (b) under a 50% voltage sag and when $P_g \approx 175$ W showing supply, load, injected and DC-link voltages and injected active and reactive powers. (Measured by dSPACE)

change in the load voltage magnitude even as the voltage sag remains.

Fig. 6.4 compares the theoretical calculated $t_{max,k,l,m}$ based on (6.20) with those obtained from the various test measurements. It can be seen that the two sets of results agree amicably well. The small discrepancies can be attributed to the uncertainty in the system parameters used in the theoretical calculation. Fig. 6.4

Fig. 6.4 Comparison between the theoretical and experimentally measured $t_{max,k,l,m}$ for various sag magnitudes and P_g .

clearly shows that with a larger P_g , the ability of the DRG-ESS in load LVRT improves: for example, for $P_g \approx 205$ W, $t_{max,k,l,m} = 1.13$ sec for $V_s = 0.2$ p.u. whereas under no-sun condition, $t_{max,k,l,m}$ will be reduced to 0.1 sec. Furthermore, the DRG could support load LVRT continuously for voltage sag of up 74%, i.e. successful LVRT is possible for $V_s \geq 0.26$ p.u., if P_g is higher than 205W.

6.4. Statistical Approach to Optimize DRG-ESS Capacity

The analysis and experimental result clearly demonstrate that an increase in the harnessed power P_g (and therefore higher capacity of the DRG) and the energy capacity of the capacitor ESS will lead to higher load LVRT capability. Such voltage quality enhancement is desirable, although the extent of the gain depends very much on the severity of voltage sag and load sensitivity to the sags. Also, the enhancement is achieved at the expense of an increase in cost of the DRG-ESS.

In this section, a simple approach is suggested as a possible method to optimize the capacity of the DRG-ESS through the maximization of the performance index

$$\lambda = B_R \times \sum_k [prob(RT | V_{s,k}) \times N_k \times w_k] + B_G - C_{ESS} - C_{RG} \quad (6.21)$$

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λ is to be maximized through a search process to yield the optimal DRG-ESS capacity. In (6.21), B_R denotes the economic benefit when a successful load LVRT is achieved, while N_k denotes the number of sag events with magnitude $V_{S,k}$ per year. In this context, $prob(RT | V_{S,k})$ is the probability of successful ride-through in a year for given sag magnitude and it can be determined using (6.11) for a given DRG-ESS capacity. w_k is the weighting factor which, when multiplied by $prob(RT | V_{S,k})$, yields the number of weighted sag event which has been mitigated successfully. Summation of these weighted events produces the total number of weighted events which have been ridden-through successfully by the load in a year. This method of using weighting factors to reflect the benefits of sag mitigation, in accordance to the severity of the voltage sags, is similar to that shown in [246]. The next term B_G denotes the total economic benefit of energy harnessed and exported by the DRG-ESS in a year. Thus the first two terms on the RHS of (6.21) reflect the benefits of having the DRG-ESS performing as a generator as well as a series compensator which enhances load LVRT capability. The remaining terms, C_{ESS} and C_{RG} , denote the annualized cost of the ESS and DRG respectively. Hence, λ provides a measure of the annualized net benefit of incorporating the DRG-ESS in the power system. The maximization of λ shall produce the optimal capacity of the DRG-ESS.

6.5. Numerical Examples

In this Section, the proposed statistical approach is used to assess the performance of the DRG-ESS shown in Fig. 6.2. Parameters of the electrical system are the same as those used in the experimental prototype described in Section 6.3.2. In assessing load LVRT, the voltage sag probability distribution $prob(V_{S,k}, t_S)$ is assumed similar to that shown in [41].

6.5.1. Preliminary Data Preparation

As alluded to in Section 6.2.1 and using the solar insolation level recorded in the author's campus, the harnessed photovoltaic power P_g was determined. The sensitive load demand (P_L) was assumed to exhibit the same pattern as that of Singapore system-wide load given in [196]. Thus the marginal distributions of P_g and P_L were

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determined and their mass probabilities are as shown in Fig. 6.5(a) and Fig. 6.5(b) respectively. Clearly P_g and P_L are not normally distributed and hence, the conventional approach to analyze dependency between two normally-distributed RV is not applicable in this instance.

Fig. 6.6 shows a typical weekly recorded solar irradiation and load profiles. It shows that in Singapore, instances of the maximum insolation level tend to coincide with

Fig. 6.5 Probability distribution of (a) photovoltaic power P_g and (b) load power P_L .

Fig. 6.6 Typical weekly profiles of solar irradiation and load.

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periods of daily load peak and the minimum load demand occurs at nighttime (i.e. zero insolation level). The figure clearly shows some degree of correlation between P_g and P_L .

Therefore in order to obtain their joint probability distribution, the recorded P_g and P_L data was transferred to the rank domain using the corresponding marginal CDFs and the dependence structure between them was measured using rank correlation. The computed rank correlation $\rho_r=0.59$ was inputted into several commonly used copula functions, in the manner as explained in Section 6.2.3, to develop a set of correlated P_g and P_L . The developed set of P_g and P_L from each copula function are transformed back from the rank domain to the actual domain using the inverse CDF. The outcome is a data-set of P_g and P_L obtained from simulation using the particular copula function. The statistical compatibility between the simulated and actual distributions of P_g and P_L was then assessed via the KS test. In this example, the Gumbel, Frank and Gaussian copulas passed the KS test with a significance level of 1%. The Gumbel copula was chosen for calculating the joint CDF of P_L and P_g , although the other types of copulas could also be used.

The scatter diagrams of simulated P_g and P_L using the Gumbel copula and that from

Fig. 6.7 Scatter diagrams of (a) simulated P_g vs P_L obtained using Gumbel copula; (b) ranks of simulated P_g vs P_L using Gumbel copula with $\rho_r=0.59$.

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the rank domain of the simulated P_g and P_L are illustrated in Fig. 6.7(a) and 6.7(b) respectively. Their calculated rank correlation is 0.59. The monotonic relation between P_g and P_L can be observed from their corresponding ranks along the diagonal of Fig. 6.7(b). It shows the stochastic dependency of P_g and P_L .

Fig 6.8(a) shows the resulting joint CDF of P_L and P_g obtained by applying the Gumbel copula in (6.13). The joint probability of P_g and P_L (i.e. $prob(P_g, P_L)$) was then calculated from the joint CDF and the results are as shown in Fig. 6.8(b).

Fig. 6.8 (a) Joint CDF of P_g and P_L . (b) Joint probability of P_g and P_L .

6.5.2. Probability of Voltage Sag Ride-through

With $prob(P_g, P_L)$ determined, the probability of successful voltage sag ride-through was then determined for different P_L using (6.9). The results are summarized in Fig. 6.9(a). Some interesting observations can be deduced from the figure. Firstly, it shows the probability of successful voltage sag ride-through consistently increases with P_L over periods of heavy load conditions when $P_L > 0.85$ pu. The reason for this is because the heavy load condition tends to coincide with instances of high solar insolation. This can be seen in Fig. 6.6. Thus there is high probability the DRG can contribute sufficient P_g to mitigate the voltage sags during periods of heavy load,

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Fig. 6.9 (a) Probability of load LVRT vs P_L (b) Probability of load LVRT vs E_S for C_{DC} of different energy storage capacity.

even when the energy storage capacity is negligible. In contrast, at low load level of some 0.56 - 0.63 p.u., the probability of successful load LVRT actually decreases as the load increases when the ESS capacity is low. This is because low load occurs at night and early morning when the solar insolation level is zero, again as can be seen from Fig. 6.6. Thus the ability of the DRG-ESS to support load LVRT reduces with P_L although this reduction can be mitigated with an increase in the energy storage capacity of C_{DC} . Fig. 6.9(b) shows the probability of load LVRT with various capacitor storage capacities. As expected, the probability of successful load LVRT decreases with the severity of voltage sags. However, the load LVRT capability afforded by the DRG-ESS shall be significantly enhanced through a modest increase of the ESS storage capacity and even under the most severe voltage sags.

In order to further explore the design of the most effective DRG-ESS, load LVRT was examined for DRG-ESS with a range of power and energy storage capacities. Fig. 6.10 summarizes the results obtained from the study. It shows that while the higher capacity of C_{DC} has greatly improved load LVRT, an increase in the installed capacity of the PV arrays also improves the load LVRT. For example, to achieve a load LVRT probability of 0.95 will require C_{DC} of 8.26mF if there is only one PV

Fig. 6.10 Probability of load LVRT for different installed P_{PV} at various capacitances.

array (rated 323 VA). With two such PV arrays, the required C_{DC} reduces to 2.23 mF. Without the contribution of the sun, however, a 11.38 mF C_{DC} is needed to meet the same probability of load LVRT. It should be noted that in order to utilize the higher capacity of the PV generator, V_{DC} must be increased. Therefore some proportion of the load LVRT improvement with the two PV arrays can be attributed to the increase in the amount of energy stored in C_{DC} due to the higher V_{DC} .

Also, it will be interesting to compare the results of Fig. 6.10 with that obtained from conventional deterministic approach in which the design of the DRG-ESS could be based on worst-case scenario of maximum load, during nighttime (no sun) and under the most severe sag of (say) $V_S = 0.1$ p.u., $t_S = 1$ sec. Substituting these parameters into (6.20), it shows C_{DC} of 93.2 mF is needed if the DRG-ESS is to maintain load voltage at 1 p.u. and there is only one PV array. With this capacitance and based on the same statistical data of sag events given in [41], the DRG-ESS is able to mitigate 96.7% of the sag events. However, from Fig. 6.10 and for load LVRT probability of 96.7% and with one PV panel, a much smaller C_{DC} of 14.7 mF would be sufficient.

6.5.3. Optimized DRG-ESS Design

Next, the proposed statistical approach presented in Section 6.4 can be utilized to determine the optimal design and achieve a balance between the cost of C_{DC} , PV capacity and the economic benefit of energy harness and load LVRT. Suppose for sag event $V_S < 50\%$, the corresponding weighting factor $w_k = 0.8$, while that for $50 < V_S < 70\%$, $w_k = 0.4$ and for $70 < V_S < 90\%$, $w_k = 0.1$. These weighting factors were obtained from [246]. Assuming the cost of the ESS (i.e. C_{DC}) is linear with respect to the capacitance, consider a range of DRG capacity of up to 646VA when the annualized cost components are $C_{ESS} = 8.87$ \$/mF, $C_{RG} = 27.15$ \$/kW, and the total economic benefit of energy export by the DRG in a year (B_G) is calculated based on energy tariff of 0.22 \$/kWh. The net benefit λ is then studied as a function of C_{DC} and PV power/energy capacity. To facilitate comparison, the costs and benefits are normalized with respect to the maximum λ obtainable and the results are summarized in Fig. 6.11. It shows that when the PV capacity is rated at 646VA (2 p.u.), λ is maximum when C_{DC} is about 5.5 mF. Furthermore, as the benefit of the load LVRT becomes more significant relative to the benefit of energy harness, as reflected by an

Fig. 6.11 Profit function of LVRT versus ESS and Installed PV capacity for different B_R .

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increase in B_R , the figure shows that selecting larger C_{DC} is more profitable as λ consistently increases for a given capacity PV. For a given installed PV, there is a maximum net benefit point whereby increasing the ESS capacity i.e. C_{DC} beyond this point will not lead to an economically prudent design.

6.6. Conclusions

As the generated power from DRG, sag occurrence and load demand are random variables, a new statistical approach has been proposed in the analysis of the ability of DRG-ESS in enhancing load LVRT. P_g , V_S and P_L are treated as non-normally distributed and copula function has been used to model the correlation between P_g and P_L . The probability of load LVRT is thus derived in terms of the probability distributions of P_g , V_S and P_L . Load LVRT capability is then studied by referring to a specific series-connected PV generator constructed in the author's laboratory. Analysis shows that for this particular DRG system, load LVRT ability increases at period of heavy load. This is because in Singapore, peak load period tends to coincide with times of high solar insolation level. Statistical analysis based on the copula function enables this dependency to be studied. The proposed approach also helps to quantify the impact of energy storage capacity in the capacitor ESS in influencing the load LVRT capability afforded by the DRG-ESS. From the proposed optimal DRG-ESS design approach, it is shown that a judicious selection of the power/energy capacities of the DRG and ESS can significantly improve load LVRT and realize maximum economic benefit.

Chapter 7. Conclusions and Recommendations

7.1. Conclusions

The demand for electrical power is increasing steadily around the world but due to the negative impact of fossil fuel on the environment and global climate, developing a secure and sustainable renewable energy supply has attracted much attention. Among the renewable energy sources, PV power generation has shown excellent potential to be one major source of electricity production in the years to come because of the consistently lower price of PV cells, its low maintenance requirements, flexibility of usage and the energy production is environmentally friendly. However, integrating renewable generators into grid creates new technical challenges such as power quality, because of the intermittency and uncertain behaviors of the renewable sources. In this research work, some of these technical challenges have been brought into focus in Chapter 2 where a short review of some of the common power quality problems is presented. Power quality survey showed that the voltage sag is one of the most frequent and harmful event in distribution systems. Conventional techniques for mitigating the impacts of voltage sags and swells are reviewed. It was shown that in strong power system, series compensation is more effective than shunt compensation in maintaining voltage level during the voltage disturbances. Using DRG to enhance power quality is also described in the chapter. To overcome the adverse effect of voltage disturbances associated with DRGs or upstream grid fault, LVRT capability to be provided to load by the DRG should be incorporated into future generation of PV generators. Particular attention has been paid to series-connected PV generator, which proves to be a more effective power quality enhancing device in stiff power system (e.g. Singapore grid) than conventional shunt-connected PV generator.

A series-connected solar power generator (SPVG) has been proposed in Chapter 3. The proposed SPVG is able to maximize harnessed solar power to meet load demand as well as to improve voltage quality at the load terminal. Specifically, load voltage quality is enhanced even as the solar insolation varies and under upstream fault

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disturbance conditions. In this chapter, it was assumed that the load impedance and power factor are constant. During the voltage quality enhancement process, the analytical equations governing power flows of the device have been derived. Based on these expressions, operational principles for the SPVG were developed. Control strategy for maintaining load voltage was developed, including situations during the upstream voltage sags/swells. In order to contemplate the apparent power rating limitations of the SPVG during normal and grid fault operation states, the capability curve of the SPVG was derived. It was then established that for a given sag severity, there exists a minimum active power injection level below which load ride-through is not possible. In the case of voltage swell, higher solar power injection will in fact reduce the SPVG ability to mitigate the impact of the swell. Based on the above observation, it was concluded that an energy storage system would be necessary to enhance the load ride-through capability of the SPVG. A method to determine the capacity of the DC-link capacitor, in its role as an energy storage device, was included. Simulation results have demonstrated that the SPVG has behaved as predicted by the analytical model in contributing toward power quality improvement. The effectiveness of the DC-capacitor energy storage device in enhancing the performance of the SPVG has been clearly demonstrated, especially in situations of low insolation level or nighttime. Based on intensive simulation carried out in Chapter 3, it was shown that the SPVG is able to maintain voltage quality during voltage sag/swell and in the presence of grid voltage harmonics, as well as in maintaining load voltage constant during normal grid condition when the solar insolation level varies.

The hardware prototype realization of proposed SPVG has been presented in Chapter 4. The prototype has been implemented and tested in the author's laboratory. A microcontroller was designed to achieve MPPT for maximizing the captured energy from the sun, operating in conjunction with an inverter controller, a PLL and DFT for grid synchronization and voltage sag detection. The results of the analytical model as well as the simulation results are in good agreement with the experimental test results. Under normal grid condition, the SPVG has shown its ability to maintain the load voltage even as the solar irradiance varies. The beneficial

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effect of the capacitor energy storage device in enhancing the performance of the SPVG has also been clearly demonstrated through the experimental measurements. The test results reveal that the SPVG can successfully support load LVRT and voltage swells, and reduce the level of harmonic voltage distortions at the load terminal.

In Chapter 5, the predicted maximum duration of successful load LVRT at different level of voltage dips has been compared with the experimental results obtained from tests carried out on the prototype. The accuracy of theoretical calculations has been validated by this comparison.

Due to the random behavior of the solar irradiance, the occurrence of voltage sag and load variations, design of SPVG-ESS using conventional deterministic approach based on “worst-case” scenario which can lead to the over design of the ESS. Thus a new statistical methodology was adopted in Chapter 5 to assess the ability of SPVG in mitigating the impacts of the voltage disturbances. In this chapter, it was assumed that the load and photovoltaic power are independent random variables. The proposed statistical approach can quantify the effect of the ESS capacity on the load LVRT capability afforded by the SPVG. The analysis shows that appropriate sizing of capacitor ESS can enhance the possibility of successful load voltage restoration. The capacitor has greatly improved the probability of load LVRT, although this probability decreases with the increase in load level. Furthermore, some capacitor internal parameters may influence of load LVRT ability of the SPVG. The equivalent series resistance (ESR) of the capacitor is highly dependent of the capacitor internal temperature. Thus a method is adopted to estimate the internal temperature of the DC-link capacitor and consequently the ESR according to the operating state of the SPVG. Also, the ESR increases due to capacitor internal power losses, although the capacitance is almost constant except near the end of the capacitor life when the capacitance would decrease significantly. These parametric changes on capacitor ESS reduce the ability of the SPVG to maintain voltage quality. Thus the effect of capacitor energy storage aging on the load LVRT capability was considered in this chapter. As expected, the ideal case of a lossless capacitor ESS is shown to result in

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the highest probability of load LVRT, as compared to the cases in which losses have been included. The capability of the SPVG to mitigate of the voltage sag decreases when the load increases because heavier loads require larger amount of stored energy for successful load LVRT and moreover, the losses in the inverter and capacitor increase with the load.

The probabilities of the load LVRT using a new capacitor, an end-of-life capacitor and the ideal lossless SPVG have been calculated. The ideal lossless SPVG model consistently predicts highest probability of load LVRT but this model cannot be relied on to predict the actual performance of the SPVG. On the other hand, the more realistic SPVG model proposed in this investigation provides more reliable information on the design of the SPVG. Thus in order to have a certain level of LVRT during the life time of capacitor, the capacity reduction and the increase in ESR must be taken into account. It is necessity to obtain accurate model to identify key ESS parameters and variation of these parameters with the age of the ESS. Another observation is that as the capacitance of the capacitor increases, the respective probability of successful load LVRT for an ideal, a new capacitor and an end-of-life capacitors tend to be similar because power loss becomes increasingly less significant compared to the stored energy capacity of the capacitor. Consequently, power loss has less of an impact on the load LVRT capability afforded by the SPVG. It is observed that using statistical approach to design the ESS to achieve certain degree of likelihood of load LVRT has resulted in much smaller capacitance ESS, compared to that based on deterministic approach.

Chapter 6 proposes a new methodology for analyzing the ability of distributed renewable generator-ESS in enhancing load LVRT. The load, renewable power and grid voltage disturbances could be non-normally distributed random variables. Assuming normal distribution of the variables has been a well-established approach to deal with the design problem but it fails to take into consideration the dependency between the variables and when they are not normally-distributed. Thus a method to model the correlation between the non-normal random variables was proposed using copulas function. The probability of load LVRT in its general form was derived in

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terms of discrete probability distribution of load, voltage sag occurrence and renewable power of the DRG. It was observed that for the particular example shown in Chapter 6, the load LVRT ability of the SPVG improves at heavy load conditions because usually the peak load corresponds to high solar irradiance in daytime. The likelihood of load LVRT at instances of low-medium load demands decreases because usually the low-medium load coincides with low irradiance circumstances at the early morning and evening periods. These findings differ from what was obtained from the case that load and irradiance were assumed independent random variables in Chapter 5 in which the load demand and solar irradiance are assumed uncorrelated. Therefore by considering the correlation between the load and P_{PV} can result in different load LVRT capability by the DRG-ESS and this needs to be taken into account when designing the DRG-ESS. The proposed approach also helps to quantify the impact of energy storage capacity in the capacitor ESS in influencing the load LVRT capability afforded by the DRG-ESS. The higher capacity of C_{DC} has greatly improved load LVRT, an increase in the installed capacity of the PV arrays also improves the load LVRT. Without the contribution of the sun, the capacity of C_{DC} needed to meet the given load LVRT has to be much higher. It was observed that the probability of successful load LVRT decreases with the severity of voltage sags. Nevertheless, the load LVRT capability shall be significantly enhanced through a modest increase of the ESS storage capacity and even under the most severe voltage sags.

Although choosing the higher capacity of ESS can lead to higher load LVRT ability, the net benefit of incorporating DRG-ESS is a tradeoff between the benefit of harnessed energy, the number of load LVRT, severity of voltage sag which can be mitigated and the cost of the DRG-ESS. A simple approach was suggested in Chapter 6 to optimize the capacity of the DRG-ESS through the maximization of a performance index. Weighting factors have been used in the calculation of the performance index to reflect the benefits of sag mitigation, in accordance to the severity of the voltage sags. The total annual economic benefit of energy harnessed by the DRG-ESS is taken to account in the index as well. The annualized cost of the ESS and DRG should be subtracted from the benefits of using the DRG. Hence, the

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performance index (λ) provides a measure of the annualized net benefit of incorporating the DRG-ESS in the power system. The maximization of λ shall give the optimal capacity of the DRG-ESS. As the benefit of the load LVRT becomes more significant compared to the benefit of exported energy to the grid, choosing larger C_{DC} is more profitable as λ consistently increases for a given capacity PV. Analysis shows that there is a maximum net benefit point whereby increasing the ESS capacity beyond this point will not lead to an economically desirable design.

7.2. Recommendations

In this thesis, several new ideas have been proposed and developed for power quality enhancement using series-connected DRG.

Based on the findings acquired from the research work, a few recommendations for future work are given as follows:

- The SPVG used in this study is a single-phase device and the power rating is relatively small because of its intended application is in LV distribution system. For higher power SPVG, other type of energy storage such as super-capacitor or hybrid energy storage can be investigated. Furthermore, exploring suitable controller for 3-phase applications is necessary for high power application. The proposed technique for improvement of voltage quality could be extended for other type of renewable energies such as wind, wave and tidal energies or a hybrid version of these sources. This should be a fruitful area for future work.
- In order to study the aging effect on capacitor, a model proposed in [234, 235] has been used but the limitation of this method is that capacitance reduction due to aging cannot be analytically determined. It was assumed that the ESR and capacitance are almost constant until near the end of life of the capacitor. Therefore in the present research, new and end-of-life capacitors have been studied but the capacitor parameters between these two operating states cannot be determined accurately. So a method which can predict much more accurately the capacity of the capacitor would be an area of further investigation. This model can be used for more accurate design of ESS.

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Exploring the potential of an online monitoring system to track changes in important parameters of the capacitors such as ESR, C_{DC} and C_2 can be another area of study. The monitoring system could be coupled to an intelligent diagnostic system to track the parametric changes and the DRG-ESS control system adjusted its control actions accordingly to accommodate the changes. In the case of deploying other type of energy storage, evaluating the aging effects on energy capacity of ESS is necessary in order to design a more reliable DRG-ESS.

- The control strategy for the proposed SPVG is based on the assumption of constant load $P_L + jQ_L$. In practice, load can vary during the transient stage of the voltage restoration process. Thus by including the dynamic change of load will require the modification of the present method to design the controller so as to maintain load voltage constant. Development of an algorithm to predict the variations of the load can be another area for further work.
- The investigation on impact of non-linear loads and suppression of resulting harmonic distortions can be another fruitful area of research. Theoretically, series compensator can operate as an active filter to reduce the harmonic distortion caused by the loads but as the SPVG or series connected DRG-ESS are also renewable power harvesting systems, then the incorporation of the additional active power filtering function can be interesting.
- The probabilistic method to design the DRG was examined for the SPVG. The proposed technique can be readily extended to shunt-connected PV generator. A comparison between the capacity of shunt and series generators which have been designed through probabilistic method would be another area of fruitful research.
- In Chapters 5 and 6, it was assumed that voltage sag occurrence is independent from the load demand and the renewable power. This is a reasonable assumption in most cases. However, in locations with overhead power distribution lines, adverse weather condition can be the main cause of faults in

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the grid. So correlation between voltage disturbances and renewable sources such as wind and PV should be considered in the probabilistic evaluation of load LVRT capability offered by the DRG-ESS. Extending the current analysis to evaluate the probability of load LVRT in Chapter 6 which in turn can model dependency of voltage disturbances and renewable source is therefore recommended.

- Due to series-connection of the PV inverter, any inverter failure may disrupt power flows into the load. So developing a highly reliable inverter topology could be another aspect for future work. Increasing the inverters lifetime needs further investigation, possibly involving factors such as the daily maximum-temperature, the number of semiconductor switches and passive elements involved in the design, and especially electrolytic capacitors. This is with the view to achieve long lifetime and higher reliability of the designed SPVG.

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Appendices

APPENDIX A Parameters of Power System and SPVG

The parameters of power system and SPVG used in simulation and experimental test set-up of different chapters are presented in the following tables:

Table A.1 Parameters of Power System and SPVG in Chapter 3 and 4

Parameters	Value
Supply Voltage V_S and Load Voltage V_L	220 V (1pu)
Transformer no load loss	25 W
Transformer series impedance	4.13 Ω
Transformer turns-ratio n	1:2
Load rated power S_L	432 VA (1pu)
Load rated power factor	0.8 lagging
DC-link voltage $V_{DC,n}$	200 V
DC-link capacitor C_{DC}	7.0 mF
Filter inductance L_f and filter capacitance C_f	7 mH & 30 μ F
Input capacitance of boost Converter C_{PV}	2.4 mF
Boost Converter Inductance L	10 mH
PV module type	GL130
PV module short circuit current (1000 W/m ² , 25	3.4 A
PV module open circuit voltage (1000 W/m ² ,	18 V
PV module maximum power (1000 W/m ² , 25°C)	45 W
Latitude and longitude of PV array	1° 20' 32.5"N 103° 40' 49.8"
DC-link PI controller proportional coefficient k_p	5
DC-link PI controller integrator coefficient k_i	0.5
Inverter controller proportional coefficient K_v	40

Table A.2 Parameters of Power System and SPVG in Chapter 5

Parameters	Value
Supply Voltage V_S , Load Voltage V_L	100 V (1pu)
AC supply rating	12 kVA
Load rated power S_L	323 VA (1pu)
DC-link voltage V_{DC}	160 V
DC-link capacitor C_{DC} for new capacitor.	5.42 mF
Dielectric loss capacitor C_2 of new capacitor.	127.5 mF
R_0+R_I at 25° C for new capacitor.	0.056 Ω
R_2 for new capacitor.	0.4062 Ω
Filter inductance L_f	7 mH
Filter capacitance C_f	30 μ F
Filter resistance R_f	1 Ω
Input capacitance of boost Converter C_{PV}	2 mF
Boost Converter Inductance L_B	10 mH
PV module type	GL130
Short circuit current (1000 W/m ² , 25° C)	3.4 A
Open circuit voltage (1000 W/m ² , 25° C)	18 V
Maximum power (1000 W/m ² , 25° C)	45 W

APPENDIX B Derivation of Equation (2.11)

In this section, the mathematical derivation of (2.11) is described in details.

The shunt compensator injected current is given as

$$I_i = \sqrt{\left(I_L \cos(-\varphi) - \frac{E_S}{Z_S} \cos(\delta - \beta) + \frac{V_L}{Z_S} \cos(-\beta) \right)^2 + \left(I_L \sin(-\varphi) - \frac{E_S}{Z_S} \sin(\delta - \beta) + \frac{V_L}{Z_S} \sin(-\beta) \right)^2} \quad (2.11)$$

Then $(I_i)^2$ can be obtained from (2.11)

$$(I_i)^2 = \left(I_L \cos(-\varphi) - \frac{E_S}{Z_S} \cos(\delta - \beta) + \frac{V_L}{Z_S} \cos(-\beta) \right)^2 + \left(I_L \sin(-\varphi) - \frac{E_S}{Z_S} \sin(\delta - \beta) + \frac{V_L}{Z_S} \sin(-\beta) \right)^2 \quad (B.1)$$

To find the minimum injected current is

$$\frac{\partial I_i}{\partial \delta} = 0 \quad (B.2)$$

So derivative (B.1) with respect to δ is

$$2I_i \frac{\partial I_i}{\partial \delta} = 2 \left(I_L \cos(-\varphi) - \frac{E_S}{Z_S} \cos(\delta - \beta) + \frac{V_L}{Z_S} \cos(-\beta) \right) \times \left(\frac{E_S}{Z_S} \sin(\delta - \beta) \right) + 2 \left(I_L \sin(-\varphi) - \frac{E_S}{Z_S} \sin(\delta - \beta) + \frac{V_L}{Z_S} \sin(-\beta) \right) \times \left(-\frac{E_S}{Z_S} \cos(\delta - \beta) \right) = 0 \quad (B.3)$$

If $I_i \neq 0$, then one can have:

$$\left(I_L \cos(-\varphi) - \frac{E_S}{Z_S} \cos(\delta - \beta) + \frac{V_L}{Z_S} \cos(-\beta) \right) \times \left(\frac{E_S}{Z_S} \sin(\delta - \beta) \right) + \left(I_L \sin(-\varphi) - \frac{E_S}{Z_S} \sin(\delta - \beta) + \frac{V_L}{Z_S} \sin(-\beta) \right) \times \left(-\frac{E_S}{Z_S} \cos(\delta - \beta) \right) = 0 \quad (B.4)$$

Then by doing some mathematical regrouping one can write

$$\left(\begin{aligned} &I_L \cos(-\varphi) \times \frac{E_S}{Z_S} \sin(\delta - \beta) - \frac{E_S}{Z_S} \cos(\delta - \beta) \times \frac{E_S}{Z_S} \sin(\delta - \beta) + \\ &\frac{V_L}{Z_S} \cos(-\beta) \times \frac{E_S}{Z_S} \sin(\delta - \beta) \end{aligned} \right) + \left(\begin{aligned} &-I_L \sin(-\varphi) \times \frac{E_S}{Z_S} \cos(\delta - \beta) + \frac{E_S}{Z_S} \sin(\delta - \beta) \times \frac{E_S}{Z_S} \cos(\delta - \beta) \\ &-\frac{V_L}{Z_S} \sin(-\beta) \times \frac{E_S}{Z_S} \cos(\delta - \beta) \end{aligned} \right) = 0 \quad (\text{B.5})$$

$$\begin{aligned} &I_L \frac{E_S}{Z_S} \cos(-\varphi) \times \sin(\delta - \beta) - I_L \frac{E_S}{Z_S} \sin(-\varphi) \times \cos(\delta - \beta) \\ &- \left(\frac{E_S}{Z_S} \right)^2 \cos(\delta - \beta) \sin(\delta - \beta) + \left(\frac{E_S}{Z_S} \right)^2 \sin(\delta - \beta) \cos(\delta - \beta) \\ &+ \frac{V_L}{Z_S} \times \frac{E_S}{Z_S} \cos(-\beta) \sin(\delta - \beta) - \frac{V_L}{Z_S} \times \frac{E_S}{Z_S} \sin(-\beta) \cos(\delta - \beta) = 0 \end{aligned} \quad (\text{B.6})$$

After some mathematical manipulation, one obtains

$$\begin{aligned} &I_L \frac{E_S}{Z_S} \cos(-\varphi) \times \sin(\delta - \beta) - I_L \frac{E_S}{Z_S} \sin(-\varphi) \times \cos(\delta - \beta) + \\ &\frac{V_L}{Z_S} \times \frac{E_S}{Z_S} \cos(-\beta) \sin(\delta - \beta) - \frac{V_L}{Z_S} \times \frac{E_S}{Z_S} \sin(-\beta) \cos(\delta - \beta) = 0 \end{aligned} \quad (\text{B.7})$$

Using trigonometric function identities such as angle sum and difference at (B.7), one results in

$$I_L \frac{E_S}{Z_S} \sin(\delta - \beta + \varphi) + \frac{V_L}{Z_S} \times \frac{E_S}{Z_S} \sin(\delta) = 0 \quad (\text{B.8})$$

Again using mathematical manipulation and angle sum and difference identities one can write

$$I_L \frac{E_S}{Z_S} \sin(\delta) \cos(-\beta + \varphi) + I_L \frac{E_S}{Z_S} \cos(\delta) \sin(-\beta + \varphi) + \frac{V_L}{Z_S} \times \frac{E_S}{Z_S} \sin(\delta) = 0 \quad (\text{B.9})$$

(B.10) can be derive from (B.9) doing factorization and trigonometric identities

$$\left(I_L \frac{E_S}{Z_S} \cos(-\beta + \varphi) + \frac{V_L}{Z_S} \times \frac{E_S}{Z_S} \right) \sin(\delta) + I_L \frac{E_S}{Z_S} \cos(\delta) \sin(-\beta + \varphi) = 0 \quad (\text{B.10})$$

$$\tan(\delta) = \frac{I_L \frac{E_S}{Z_S} \sin(\beta - \varphi)}{I_L \frac{E_S}{Z_S} \cos(\beta - \varphi) + \frac{V_L}{Z_S} \times \frac{E_S}{Z_S}} = \frac{Z_S I_L \sin(\beta - \varphi)}{Z_S I_L \cos(\beta - \varphi) + V_L} \quad (\text{B.11})$$

By solving equation (B.11), δ can be obtained easily:

$$\delta = \arctan\left(\frac{Z_S I_L \sin(\beta - \varphi)}{V_L + Z_S I_L \cos(\beta - \varphi)}\right) \quad (\text{B.12})$$

Similar approach can be used to derive equation (2.6) for series compensator.

Author's Publications

Journal Papers:

1. **N. Saadat**, S. S. Choi, and D. M. Vilathgamuwa, "A Series-Connected Photovoltaic Distributed Generator Capable of Enhancing Power Quality," *IEEE Transactions on Energy Conversion*, vol. 28,no. 4, pp. 1026-1035, 2013.
2. **N. Saadat**, S. S. Choi, and D. M. Vilathgamuwa, "A Statistical Evaluation of the Capability of Distributed Renewable Generator-Energy Storage System in Providing Load Low-voltage Ride-through", accepted for publication, *IEEE Transactions on Power Delivery*, 2014.

Conference Paper:

3. **N. Saadat**, S. S. Choi, and D. M. Vilathgamuwa, "A statistical approach to quantify the impact on voltage quality caused by PV generators," in *4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, 2011, pp. 156-161.