Distributed droop schemes for standalone and interlinked AC microgrids

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**DISTRIBUTED DROOP SCHEMES FOR STANDALONE
AND INTERLINKED AC MICROGRIDS**

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Summary

Distributed Generators (DGs), when clustered to form small microgrids, offer many advantages like resource optimization, improved power quality, stability and reliability. The formed microgrids can certainly be controlled by centralized management systems, but for widely dispersed DGs where communication links are not viable, autonomous droop schemes might be more appropriate. So far, the common objective focused by the droop schemes has been proportional power sharing among the DGs based on their respective ratings. This objective is fine if the DGs are of the same type, just like the classical control of parallel synchronous generators. It is however not the case for microgrids, where different types of DGs usually exist. Proportional power sharing based on ratings alone might therefore not be suitable for microgrids. Other factors like costs, efficiencies, pricing schedules and emission penalties should be considered, just like in most centralized cases, where power dispatch commands are usually decided from a combination of factors rather than ratings alone. The same thought has however never been tried with droop control for an autonomous standalone microgrid. To fill the shortfall, a number of cost-based droop schemes has been proposed, whose power sharing in the steady state will give rise to a lower total generation cost (TGC) for the considered microgrid when compared with the traditional droop schemes. Experimental results have verified the reduction or cost saving achieved.

Like the grouping of DGs to form a single standalone microgrid, the grouping of multiple microgrids to form a larger interlinked system is possible and likely given its more efficient reserve sharing without demanding for standby generators. The interlinked microgrids are strictly free to have their own voltages and frequencies that better match with their sources and loads. This applies to existing “standard” power grids too, where

50 Hz can be found in some countries, while 60 Hz prevails in others. Frequency of 400 Hz can also be found in aircraft supply networks. It is therefore likely to have different conditioned microgrids, whose interlinking will certainly require the insertion of interlinking power converters. Power flows through these interlinking converters must thoroughly be studied and controlled appropriately, which presently, are lacking for autonomous systems. It is hence the second objective of the thesis to investigate on autonomous droop schemes for the interlinking of converters. Proper tuning of the schemes has been suggested, whose improved performances have been verified in experiments.

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List of Abbreviations

<i>AC</i>	Alternating Current
<i>AVR</i>	Automatic Voltage Regulator
<i>CB</i>	Circuit Breaker
<i>CSI</i>	Current Source Inverter
<i>DC</i>	Direct Current
<i>DER</i>	Distributed Energy Resource
<i>DGs</i>	Distributed Generators
<i>DNO</i>	Distribution Network Operator
<i>DQ</i>	Direct–Quadrature
<i>DSP</i>	Digital Signal Processor
<i>FL</i>	Full-Load
<i>HMI</i>	Human–Machine Interface
<i>HOL</i>	Heavy Over-Loaded
<i>HT</i>	High Tension
<i>IC</i>	Interlinking Converter
<i>ICE</i>	Internal Combustion Engine
<i>IGBT</i>	Insulated Gate Bipolar Transistors
<i>LV</i>	Low Voltage
<i>MAS</i>	Multi-Agent System
<i>MC</i>	Microsource Controller
<i>MGC</i>	Microgrid Central Controller
<i>MT</i>	Micro Turbine
<i>MV</i>	Medium Voltage
<i>NL</i>	No-Load
<i>O&M</i>	Operation and Maintenance
<i>OL</i>	Over-Loaded
<i>PCC</i>	Point of Common Coupling
<i>P-f</i>	Active Power vs. Frequency
<i>PI</i>	Proportional Integrator
<i>PLL</i>	Phase Locked Loop

<i>PQ</i>	Power Quality
<i>PR</i>	Proportional Resonant
<i>PV</i>	Photovoltaic
<i>Q-V</i>	Reactive Power vs. Voltage
<i>SG</i>	Synchronous Generators
<i>SPWM</i>	Sinusoidal Pulse Width Modulation
<i>SVPWM</i>	Space Vector Pulse Width Modulation
<i>T&D</i>	Transmission and Distribution
<i>TAGC</i>	Total Active Power Generation Cost
<i>TAGC_w</i>	Total Active Power Generation Cost With No-Load Costs of DGs
<i>TAGC_{wo}</i>	Total Active Power Generation Cost Without No-Load Costs of DGs
<i>TGC</i>	Total Generation Cost
<i>TRGC</i>	Total Reactive Power Generation Cost
<i>TRGC_w</i>	Total Reactive Power Generation Cost With No-Load Costs of DGs
<i>TRGC_{wo}</i>	Total Reactive Power Generation Cost Without No-Load Costs of DGs
<i>UL</i>	Under-Loaded
<i>UPS</i>	Uninterruptible Power Supply
<i>VSC</i>	Voltage Source Converter
<i>VSİ</i>	Voltage Source Inverter
<i>WTG</i>	Wind Turbines Generators
<i>ZT</i>	Zero Transfer

List of Principle Symbols

S	Complex or Apparent power
P	Active power
Q	Reactive power
V	RMS voltage
v	Instantaneous voltage
I	RMS current
i	Instantaneous current
Z	Impedance
R	Resistance
X	Reactance
δ_x	Phase angle of node or source x
f	Frequency
S_{base}	Power base
V_{base}	Voltage base
v_{abc}	Three phase instantaneous voltage
i_{abc}	Three phase instantaneous current
C_f	Filter capacitor
L_f	Filter inductor
ω_{cut}	Filter cut-off frequency
$i_{Cf,abc}$	Current through filter capacitor

Chapter 3 and Chapter 4: Distributed Droop Scheme for Standalone Microgrid

Subscript " x " = 1,2,3 represent source, DG or converter number in a microgrid

Subscript " Y " = P – Active power or Q – Reactive power

f_x^*	Reference frequency of source/DG/converter " x "
f_x	Frequency of source/DG/converter " x "
f_{min}	Minimum frequency
f_{max}	Maximum frequency
$f_{x,max}$	Maximum frequency of source/DG " x "

$f_{x,min}$	Minimum frequency of source/DG "x"
$\Delta f_{x,off}$	Frequency off-set of DG "x"
V_x^*	Reference voltage of source/DG/converter "x"
V_x	Voltage of x source/DG/converter "x"
V_{min}	Minimum voltage
V_{max}	Maximum voltage
$V_{x,max}$	Maximum voltage of source/DG "x"
$V_{x,min}$	Minimum voltage of source/DG "x"
$\Delta V_{x,off}$	Voltage off-set of DG "x"
P_x	Active power of source/DG/converter "x"
P'_x	Normalized active power of source/DG "x"
$P_{x,max}$	Maximum active power of source/DG "x"
Q_x	Reactive power of source/DG/converter "x"
Q'_x	Normalized reactive power of source/DG "x"
$Q_{x,max}$	Maximum reactive power of source/DG "x"
S_x	Apparent power of source/DG/converter "x"
$S_{x,max}$	Maximum apparent power of source/DG "x"
m_x	Active power droop coefficient of source/DG "x"
$m_{x,L}$	Active power linear droop coefficient of source/DG "x"
$m_{x,N}$	Active power non-linear droop coefficient of source/DG "x"
n_x	Reactive power droop coefficient of source/DG "x"
$n_{x,L}$	Reactive power linear droop coefficient of source/DG "x"
$n_{x,N}$	Reactive power non-linear droop coefficient of source/DG "x"
η_x	Efficiency of inverter/converter "x"
$C_{P,x}(P_x)$	Active power total generation cost-function of DG "x"
$C_{Q,x}(Q_x)$	Reactive power total generation cost-function of DG "x"
$C_{P,x,o}(P_x)$	Active power operation and maintenance cost-function of DG "x"
$C_{P,x,\xi}(P_x)$	Active power emission penalty/incentive cost-function of DG "x"
$C_{P,x,int}(P_x)$	Active power generation cost-function of renewable DG "x" without converter losses
$C'_{P,x}(P_x)$	Active power total generation cost-function of DG "x" normalized to maximum power

$C''_{P,x}(P_x)$	Normalized active power total generation cost-function of DG "x"
$C'_{P,x}(P_x = 0)$	Active power total generation cost at no-load
$C''_{ref}(P_y)$	Normalized active power total generation cost-function of reference DG
$C''_{ref}(Q_y)$	Normalized reactive power total generation cost-function of reference DG
$C''_{ref,max}$	Normalized total generation cost of reference DG at maximum power
$C''_{P,x,max}$	Normalized total active power generation cost of DG "x" value at maximum power/full-load
$C''_{P,x}(P_{x,max})$	Normalized total active power generation cost of DG "x" value at maximum power/full-load
$C''_{P,max}$	Maximum of normalized total active power generation cost of DGs at maximum power/full-load
$C''_{Q,max}$	Maximum of normalized total reactive power generation cost of DGs at maximum power/full-load
C''_{min}	Minimum of normalized total generation cost of DGs at maximum power /full-load
$P_{Q,loss}$	Active power loss incurred due to reactive power generation
$C_{S,x}$ $(P_x + P_{x,Q,loss})$	Apparent power total generation cost of DG "x"
$C'_{Q,x}(Q_x)$	Reactive power total generation cost-function of DG "x" normalized to maximum power
$C''_{Q,x}(Q_x)$	Normalized reactive power total generation cost-function of DG "x"
$C'_{Q,x}(Q_x = 0)$	Reactive power total generation cost of DG "x" at zero/no-load
$C''_{Q,x}(Q_{x,max})$	Normalized total reactive power generation cost of DG "x" at maximum power/full-load
$C'_{Y,min}(0)$	Minimum of total (Y= active or reactive) power generation cost of DGs at zero/no-load
$C'_{Y,max}(0)$	Maximum of total (Y=active or reactive) power generation cost of DGs at zero/no-load
$C'_{Y,min}(Y_{max})$	Minimum of total (Y=active or reactive) power generation cost of DGs at maximum power/full-load
$C'_{Y,max}(Y_{max})$	Maximum of total (Y=active or reactive) power generation cost of DGs at maximum power/full-load

Chapter 5 and Chapter 6: Distributed Droop Scheme for Interlinked Microgrid

Subscript "x" = A or B Microgrid "A" or Microgrid – "B" .

Subscript "y" = 1,2,3 DG number in a Microgrid

f_x	Frequency of interlinked microgrid "x"
$f_{x,max}$	Maximum frequency of interlinked microgrid "x"
$f_{x,min}$	Minimum frequency of interlinked microgrid "x"
$f_{x,L}$	Frequency lower threshold when microgrid "x" to request power import
$f_{A,U}$	Frequency upper threshold when microgrid "x" to request power export
$f_{x,OL}$	Overload frequency threshold in microgrid "x"
$f_{x,HOL}$	Heavily overload frequency threshold in microgrid "x"
V_x	Voltage of interlinked microgrid "x"
$V_{x,max}$	Maximum voltage of interlinked microgrid "x"
$V_{x,min}$	Minimum voltage of interlinked microgrid "x"
$V_{x,OL}$	Overload voltage threshold in microgrid "x"
$V_{x,HOL}$	Heavily overload voltage threshold in microgrid "x"
$V_{x,int}$	Voltage threshold when microgrid "x" request for reactive power
P_x	Active power of interlinked microgrid "x"
P_{xy}	Active power of DG "y" in interlinked microgrid "x"
P_{IC}	Active power of interlinking converter
$P_{x,IC}$	Active power of interlinking converter "x"
$P'_{x,IC}$	Active power request by microgrid "x"
$P_{x,act}$	Active power threshold of interlinked microgrid "x"
$P_{x,IC,max}$	Maximum active power of interlinking converter "x"
$P_{x,IC}^*$	Active power transferred by interlinking converter "x"
$P_{x,IC,max}$	Maximum active power of interlinked microgrid "x" side converter
Q_x	Reactive power of interlinked microgrid "x"
Q_{xy}	Reactive power of DG "y" in interlinked microgrid "x"
Q_{IC}	Reactive power of interlinking converter
$Q_{x,IC}$	Reactive power of interlinking converter "x"
$Q'_{x,IC}$	Reactive power request by microgrid "x"
$Q_{x,IC,max}$	Maximum reactive power of interlinking converter "x"
$Q_{x,IC}^*$	Reactive power transferred by interlinking converter "x"

$Q_{x,act}$	Reactive power threshold of interlinked microgrid "x"
$Q_{x,IC,max}$	Maximum reactive power of interlinking converter "x"
$Q_{x,IC,max}$	Maximum reactive power of interlinked microgrid "x" side converter
S_x	Apparent power of interlinked microgrid "x"
S_{xy}	Apparent power of DG "y" in interlinked microgrid "x"
$S_{x,IC}$	Apparent power of interlinking converter "x"
S_{IC}	Apparent power of interlinking converter
$S_{x,IC,max}$	Maximum apparent power of interlinked microgrid "x" side converter
m_{xy}	Active power droop coefficient of DG "y" in microgrid "x"
n_{xy}	Reactive power droop coefficient of DG "y" in microgrid "x"
$m_{x,IC}$	Active power droop coefficient of interlinking converter "x"
$n_{x,IC}$	Reactive power droop coefficient of interlinking converter "x"

Appendix A: Stability Model of Droop Controlled Converters

Δ	Represents the linearized variable
dq	Script represent the values in synchronous reference frame
Δx	Linearized state variable matrix
$\dot{\Delta x}$	Linearized state variable differentiated with respect to time matrix
A_{DG}	DG finite matrix
B_{DG}	Input matrix
i_{Lf}	Filter inductor current
v_{cf}	Filter capacitor voltage
i_o	DG output current
$v_o = v_{cf}$	DG output voltage
v_{mg}	Microgrid voltage
P	DG output active power
Q	DG output reactive power
L_f	Filter inductor

C_f	Filter capacitor
R_t	Line resistance
L_t	Line inductance
ω	Microgrid frequency in radian
ω_n	Microgrid nominal frequency in radian
ω_c	Filter cut-off frequency
ω_{ref}	Droop controller output reference frequency in radian
V_{oref}	Droop controller output reference voltage
v_{dc}	DC source voltage
k_{ip}	Current controller proportional gain
k_{ii}	Current controller integral gain
k_{vp}	Voltage controller proportional gain
k_{vi}	Voltage controller integral gain

Publications

Following is the list of papers published/submitted during PhD research at Nanyang Technological University.

Conference Publications

- [1] **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Power flow control of interlinked hybrid microgrids", *In Proceedings of the 15th International Power Electronics and Motion Control Conference, Novi Sad*, pp. DS3b.17-1 - DS3b.17-6, Sept. 2012.
- [2] **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Distributed control of hybrid AC microgrids with dynamic active and reactive power capacity tuning," *IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC*, pp.1954-1959, Sept. 2012.
- [3] **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Autonomous droop scheme with reduced generation cost," *In Proceedings of the 16th International Power Electronics and Motion Control Conference, EPE ECCE-2013, Lille*. p.1-7, Sep 2013.
- [4] **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Cost-Based droop scheme with lower generation costs for microgrids," *In Proceedings of the 5th Annual International Energy Conversion Congress and Exhibition, ECCE Asia, Melbourne*, pp.339-343, June 2013,
- [5] **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Cost-prioritized droop schemes for autonomous microgrids," *IEEE Energy Conversion Congress and Exposition (ECCE), 2013, Denver, CO*, pp.1021-1025, Sep. 2013.

Transaction Publications

- [6] I. U. Nutkani, P. C. Loh, F. Blaabjerg, "Power flow control of intertied ac microgrids", *IET in Power Electronics*, vol. 6, no7, pp. 1329-1338, Sep. 2013.
- [7] I. U. Nutkani, P. C. Loh, F. Blaabjerg, "Distributed operation of interlinked AC microgrids with dynamic active and reactive power tuning," *IEEE Trans. of Indus. App.*, vol.49, no.5, pp.2188-2196, 2013.
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- [10] I. U. Nutkani, P. C. Loh, F. Blaabjerg, "Cost-based droop scheme with lower generation costs for microgrids," *IET in Power Electronics*, [IET Digital Lib DOI: 10.1049/iet-pel.2013.0243](https://doi.org/10.1049/iet-pel.2013.0243).
- [11] I. U. Nutkani, P. C. Loh, W. Peng, F. Blaabjerg, "Cost-prioritized droop schemes for autonomous microgrids," *IEEE Trans in Power Electron.* [IEEE Explorer DOI: 10.1109/TPEL.2014.2313605](https://doi.org/10.1109/TPEL.2014.2313605).

Chapter 1

Introduction

1.1 Motivation

Global demand for energy, depletion of conventional energy sources and dropping prices of new energy technologies have brought forward the concepts of distributed generation and microgrids [1]-[4]. Over the last one decade, these technologies have evolved from pilot projects to their respective commercialization stages with wide range of applications planned in both developed and developing countries. Some prospective areas of applications can be found in the commercial, institutional, military, marine, aerospace and remote communities. These rapidly growing technologies have created many research opportunities with the common goal being to strengthen the robustness, efficiency and reliability of the future power grid networks. Recent initiatives begun for smart grids in many countries around the globe have further raised the urgency to have new intelligent, reliable and efficient grid technologies [2], [5]-[7]. The future smart grids are expected to be more resilient and intelligent with many self-managing entities tied to them. These entities can be small user-end power systems, known as ‘microgrids’, which in practice, can either operate independently or tie to the utility grid. The latter can also be another microgrid, if the intention is to have better reserve sharing.

Popularity of microgrids is therefore expected to grow, which to a great extent, has motivated the creation of the two research themes studied in this thesis. The aim is to enhance the system performance, efficiency and reliability, which will probably be clearer after giving an overview of DGs and microgrids, followed by defining the problem statements for the proposed research.

1.2 Distributed Generation and Microgrids

Distributed Generation, also referred to as “Distributed Generators (DGs)” or “Distributed Energy Resources (DERs)”, is realized by compact, modular and relatively small generation sources and/or storage systems. These generators are connected directly to the distribution network, and are usually located close to the end users [8]-[10]. Strictly, distributed generation is not a new thought, and has in fact been there since the 19th century, during which electric power was first introduced and generated near to the loads. Recent interest in alternative energy and power electronic advancement have simply broadened its scope from an individual DG to multiple DGs, which can further be grouped to form microgrids and multi-microgrids, as shown in Fig. 1-1.

Distributed generation is also not restricted to a single generating method. It includes a wide range of generating technologies, including micro turbines, internal combustion engines, fuel cells, solar PV, wind power and storage. Most of these generating technologies require power electronics (converter/inverter) for interfacing with the active power distribution system [11]-[22]. These new energy technologies are more environmentally friendly, and as inventions continue to surface, they have the potential to compete with conventional technologies based on economy of scale [23]-[24].

Fig. 1-1. Paradigm shift in emerging generation system

However, a high penetration of distributed generators to the utility grid may bring along problems linked to their low inertia and intermittent sources, which also contribute to the system fault level.

A better way of coping with the identified issues is to merge the advantages of different sources and storage systems in a microgrid for powering its own loads [3], [10], [25]. An illustration of the formed microgrid is given in Fig. 1-2, where the sources and storage systems merged can either be conventional or unconventional. They may include solar PV, wind turbines, fuel cells, micro-turbines, internal combustion engines and various storage technologies like batteries, ultra-capacitors and flywheels. A microgrid therefore benefits from optimized usage of available resources, better power quality, improved stability and reliability [18], [23], [26]-[29]. Where necessary, a microgrid can also be tasked to provide additional services such as demand response management, harmonic load sharing, voltage and reactive power support [30]-[35].

Regardless of its functionalities though, a microgrid is usually designed for the low or medium voltage distribution networks since it is located close to the loads. Being an

independent module, the microgrid may also be designed with its own preferred frequency, voltage and network configuration that better suit its load requirements. Different types of microgrids may therefore surface including the less conventional dc microgrid. Viewed from another angle, different types of microgrids have actually been in existence for many years like the following few examples named below.

- Landed grids
- Remote/Rural grids
- Institutional grids
- Commercial/industrial grids
- Mobile grids
- Military grids
- Marine grids
- Aerospace grid

Fig. 1-2. Example of standalone microgrid

The quality of supply and control specifications imposed on an individual microgrid is usually determined by its source, network and load requirements. In all cases, it is ideal to have a management system for managing all its internal resources so that they cooperate in the best possible manner. Such power management system is also usually necessary for maintaining the overall stable operation and high efficiency of the microgrid. In terms of standardization, there are plenty of international and regional codes for governing distributed generation and microgrid [36]-[38], which although are useful, might not fully cover all demanded functionalities from the microgrid. These demands, in the ideal case, should mainly be decided by the sources and loads, which in practice, might not be feasible because of existing network constraints. Despite that, a few common functionalities demanded from a microgrid in its grid-connected or standalone mode can still be broadly summarized, as follows.

1. *Power Sharing*: Active and reactive power balance should be maintained on a long-term basis without over-stressing any of the generators found in the microgrid.
2. *Optimized Use of Resources*: Microgrid power management system should include some form of strategy for optimizing its resource allocation. The optimization objective can be defined as a reduction of generation cost, a lowering of environmental impact or a combination of both. In most microgrids, this objective is mainly decided by their centralized control management systems, whose details will be reviewed in a later section of this chapter.
3. *Grid-Connected and Standalone Modes*: Depending on preferences and requirements, some microgrids are planned for autonomous standalone operation only. Others can be connected to the utility grid for a better inertia support or simply because of economic gain. A comprehensive power management system

should hence be able to support both modes, including their accompanied synchronization and islanding detection.

4. *Auxiliary Services*: Apart from supplying active and reactive load demands, a microgrid might at times be required to provide auxiliary services like voltage regulation at the user end, reactive power support and harmonic load sharing.

1.3 Concept of Interlinked Microgrid

Similar to the clustering of DGs to form a microgrid, multiple microgrids at different frequencies and voltages can be clustered to form an interlinked hybrid microgrid. An interlinked microgrid can better share active and reactive powers among its entities, while allowing different frequencies and voltages to be realized for improved performance and supply reliability. Its higher system inertia also helps to keep the system stable when perturbed, while its lower reserve requirement helps to lower the startup capital cost, which in most cases, will include the cost of inserting power converters. These power converters are for grid-interfacing, energy conditioning and harmonizing of different operating conditions of the microgrids before inter-tying them. Usual line-frequency transformers can also be used, but only for different voltages and not frequencies among the microgrids. Adding of power converters is therefore a more universal approach likely to draw more interest.

Practically, inter-tying of microgrids is not an imaginary thought, judging from the number and types of microgrids already in existence. They include standalone power networks for all electric ships, all electric aircrafts and all electric vehicles. The electric power networks on these transporters are analogous to autonomous microgrids with their own preferred voltages and frequencies (e.g. frequencies of 50Hz, 60Hz and

400Hz, and voltages of 110V, 230V, 3.3kV and 6.6kV), even though they are usually compactly small [39]-[42]. The same concepts observed from these mobile microgrids can similarly be transferred to the landed microgrids, where different voltages and frequencies can be chosen for benefitting both their sources and loads in general. To a certain extent, this has already been done for existing standard power grids, where some countries have opted for 50 Hz, while others prefer 60 Hz. The same applies to voltages with different values set for different hierarchical levels in different countries. It is therefore likely to have multiple microgrids, whose voltages and frequencies are set to their respective optimized values. These microgrids can either be independent or tied together by interlinking power converters for resource sharing. An illustration showing the latter is given in Fig. 1-3.

The thought of clustering and interlinking has, in fact, been recently promoted by a research effort, concentrating on the division of a local area network into sub-zones/clusters of either the same or different voltage levels. The objective there is to enhance system reliability, security and efficiency by minimizing transmission and distribution losses. It can, in principle, be achieved by careful planning such that each cluster is self-balanced with minimum or no net energy flowing through its interlinking power converters. Power losses generated by the converters are therefore low even when ancillary services like reactive power support, fault ride-through and harmonic compensation are provided.

It is thus of interest to investigate microgrids in further details in either their individual or interlinked mode. For both modes, power flow management and control schemes will be developed, which in the ideal case, should be efficient and autonomous without demanding for fast communication links. The latter is important since distributed sources are widely dispersed, and hence costly and unreliable to link, even if possible.

Various autonomous schemes are thus developed, which for the thesis, are demonstrated with ac microgrids only. This is certainly not a restriction, but simply a possibility out of four in TABLE 1-1 chosen for demonstration.

Fig. 1-3. Example of interlinked rural/landed microgrids

TABLE 1-1: Possible interlinked hybrid microgrids architectures and applications

Architecture		Similarities/Differences		
Microgrid "A"	Microgrid "B"	Voltage	Frequency	Possible Applications
AC	AC	$V_A = V_B$	$f_A = f_B$	Landed
		$V_A = V_B$	$f_A \neq f_B$	Industrial
		$V_A \neq V_B$	$f_A = f_B$	Marine
		$V_A \neq V_B$	$f_A \neq f_B$	Aerospace
				Mobile military grids

1.4 Overview of Existing Power Sharing Control in Standalone Microgrids

Microgrid, being a combination of different resources, should preferably be controlled by a multilevel complex scheme in order to efficiently utilize its resources during its steady operational mode [43]-[45]. The control details realized will usually depend on the types of resources and applications under consideration, which in general, can still be broadly classified as the centralized and decentralized architectures. These two architectures can further be sub-categorized, as shown in Fig. 1-4. These sub-categories will be explained in subsequent paragraphs.

Fig. 1-4. Classification of microgrid control architectures

1.4.1 Microgrid Centralized Control

The control architecture chosen for a centralized system is usually hierarchical with its main sub-components identified as the DG (Generation, Storage and Load) Controllers

and Microgrid Central Controller (MGC). Where possible, the centralized scheme should be implemented because of its many advantages like better power, voltage and frequency regulation, and its ability to optimize the DG operation [43],[45]-[52]. The centralized scheme is however not free from limitations with its main concern being its reliance on extensive communication links. This is especially true for microgrids with vast number of assets, and hence large amount of data for transfer. Addition of new DGs might also require major modification, redesign or reprogramming of the MGC. The microgrid overall stability and reliability are therefore highly dependent on the communication network and ease of reprogramming the MGC, which in a way, act like single points of failure. These vulnerabilities are no doubt not attractive, which should hence be avoided where possible.

1.4.2 Microgrid Decentralized Control

Due to the drawbacks faced by centralized control system, decentralized autonomous schemes are subsequently introduced, whose main intention is to achieve independence of configuration and communication links. The resulting schemes must also be tunable to allow for expansion or modification of the system. Although a number of schemes have already been presented, their operating principles can broadly be categorized into two different approaches, whose advantages and drawbacks are discussed, as follows.

1.4.2.1 Multi-Agent Based Control

In a multi-agent based system, each DG and its functional entities (e.g. synchronization and distribution operators) have an agent associated with them like the control agent, management agent and ancillary agent. These control agents have to exchange data among themselves, and make control decisions for their respective DGs based on their

defined control algorithms [53]-[60]. The control concept can be applied through either the fully and partially decentralized approach, which in theory, allows plug-n-play expansion of the system, but still requires reliable communication links for high speed data exchange among the different agents. Multi-agent approach is thus not strictly autonomous, and can be relatively complex, even though a lot of research has already been done on it when applied to power systems and microgrids.

1.4.2.2 Autonomous Droop Control

Another way of realizing decentralized control for a microgrid is through the application of an appropriate droop scheme. Droop control has earlier been widely applied to the control of multiple large synchronous generators in conventional power systems [61], [62]. The same concept has subsequently been extended to microgrids for achieving proportional power sharing among the DGs based only on their power ratings. Droop control can therefore provide plug-n-play flexibility without demanding for a centralized controller and communication links [63], [64]. It is thus a fail-safe technique, whose key features are summarized below:

- Droop control ensures effective load management among the DGs with active and reactive powers controlled independently. Its effectiveness only degrades prominently when applied to a predominantly resistive network, usually found with LV microgrids. When that happens, coupling issues surface, whose details and solutions are reviewed in Chapter-2.
- Droop control facilitates simple expansion of the system by allowing new DGs to be added and placed at convenient locations in the network without demanding for major modification or re-engineering of the existing control.

Addition of new DGs also does not require information or data from the other DGs already tied to the microgrid.

- Droop control is comparably simpler and easier to implement than the multi-agent based control.

Despite the favorable features listed above, droop control has a few shortcomings, mainly linked to its inability to optimize the DG operation (as shown in TABLE 1-2), and its poorer voltage and frequency regulation. Presently, these shortcomings are resolved by including a secondary centralized control layer, whose dynamic is usually much slower than that of the primary droop scheme [46]-[48].

TABLE 1-2: Microgrid key control feature comparison

Microgrid Desired Control Features	Centralized Control	Traditional Decentralized Droop
Power balance	✓	✓
Optimized power dispatch	✓	✗
Standalone and grid connected operation, and auxiliary services	✓	✓
Reliable/Independent of communication links	✗	✓
Plug-n-Play (without modification/expansions)	✗	✓

1.5 Problem Statements and Proposed Research for Standalone and Interlinked AC Microgrids

1.5.1 Power Sharing in Standalone Microgrids

As mentioned above, standalone microgrids are usually controlled by an appropriate droop scheme, whose objective has almost always been defined as achieving proportional power sharing among the DGs based on their respective power ratings. This objective is fine if the DGs have the same operating characteristics or a secondary centralized system has been added to alter it (the objective), when necessary. For cases where both conditions are not met, power sharing based on ratings might not always be reasonable since other operating characteristics of the DGs should ideally be considered. Existing droop schemes are therefore not always the best choices for standalone microgrids if their DG operating characteristics vary widely. To address the concern raised, alternative cost-based droop schemes are proposed, whose control decisions are made based on various DG operating characteristics (e.g. operating costs, environmental impacts and others), rather than relying solely on the DG ratings. Details of these schemes are provided in later chapters.

1.5.2 Power Sharing in Interlinked AC Microgrids

Another concept discussed earlier is the inter-tying of two or more microgrids operating at different voltages and/or frequencies. The inter-tying is normally realized by interlinking power converters, which when controlled appropriately, can bring along many potential benefits to the interlinked system. They include reduced reserve requirements in each individual microgrid, enhanced reactive power generation contributed by the interlinking converters, and improved voltage and frequency support

experienced by the interlinked system. These benefits are obviously not naturally occurring. They must instead be ensured by a properly designed power management scheme, whose responsibility is to manage the power flowing through the interlinking converters. Overall, the interlinked system will hence be more robust with better ride-through and reserve supports without demanding for fast communication links. The latter is particularly important to distributed generation, whose sources are mostly dispersed, and hence costly or impossible to link by a vast communication network. The second theme defined is thus to study the interlinking power transfer among multiple microgrids, which presently, is a scope not covered by existing autonomous droop schemes.

1.6 Research Objectives

Broadly, the scope of work defined is to develop new distributed droop schemes for standalone and interlinked microgrids. The goal is to have higher efficiency and better performance, whose point-by-point related objectives are summarized, as follows.

- *To develop power sharing schemes with the DG operating characteristics considered:* For standalone microgrids, where centralized management is not viable, alternative droop schemes should be developed with the DG operating characteristics taken into consideration. The outcome is a fairer sharing of power among the DGs based on their different operating characteristics, rather than relying only on their ratings.
- *To develop power flow management schemes for interlinked microgrids:* Control schemes for managing power flows through interlinking converters are presently lacking. Suitable control schemes must be implemented before the inter-tied

microgrids can be coordinated to share active power reserves and enforce reactive power support in an efficient manner.

- *To ensure that the schemes developed are all autonomous and suitable for distributed usage:* This criterion is important to microgrids, whether operating as an individual standalone or interlinked system. It is especially true for microgrids with widely dispersed sources that are hard to be linked by a communication network. Omission of the communication might also be preferred for systems with high reliability requirements since its failure might bring down the whole system.
- *To verify the proposed schemes through experimental testing:* A suitable scaled-down experimental system has been designed for testing in the laboratory. The terminal voltages and currents sensed have been fed to the digital signal processors of the relevant DGs for computing the active and reactive powers generated or transferred. These power values are used for both control and monitoring purposes.

The above objectives are met by a number of new distributed droop schemes proposed in the thesis, whose brief descriptions are provided in the next immediate section.

1.7 Thesis Contributions

Contributions made in this thesis are mainly in the scope of developing new distributed droop schemes for standalone and interlinked ac microgrids. The schemes proposed for standalone microgrids have prominently shown a reduction of generation costs for the microgrids when compared with the existing droop schemes. Other generation objectives or weighted combination of objectives can also be met, if desired, without any requirement for complex management and fast communication links among the

widely dispersed DGs. The schemes have almost fully been developed from generic principles, and can hence be applied to different microgrids with different types of DGs and operating characteristics. They have so far not been investigated by other researchers, and are expected to pave new research paths for future investigation.

The same generic approach has been followed when developing droop schemes for interlinked ac microgrids. The outcomes anticipated are thus their wide applicability, improved reserve sharing among the microgrids, stronger voltage support and enhanced generation support due to the additional reactive power generation contributed by the interlinking converters. The concepts and control schemes proposed are also expected to strengthen understanding of requirements and implementation details relevant to the interlinking of microgrids for improving supply quality and reliability.

All schemes proposed in the thesis are autonomous, based only on locally measured parameters. They have thus retained the merits of simplicity and flexibility from the basic droop scheme. Further descriptions about contributions made within the defined scope can be found in the following text.

1.7.1 Distributed Droop Schemes for Standalone Microgrids

A number of new droop schemes have been proposed with the DG operating characteristics such as fuel operating costs and greenhouse emission penalties / incentives considered, instead of only the DG ratings. Their common aim is almost always to reduce the Total Generation Cost (TGC) of the considered microgrid, while preserving the simplicity of the basic droop scheme. Features of the schemes are briefly described here to give an overview of the content to be expected from subsequent chapters.

- *Section 3.3 of Chapter 3* : DG operating characteristics related to fuel, direct operating and greenhouse emission costs (or incentives) are thoroughly discussed. The knowledge gained is subsequently applied to formulate generic active and reactive power generation cost-functions for DGs of the internal combustion engine (ICE) and converter interfaced types. These cost-functions are eventually used for formulating the proposed droop schemes.
- *Section 3.4 of Chapter 3* : A droop scheme based on a chosen reference cost-function is proposed. The scheme considers all the DG active power generation cost characteristics, from which a reference cost-function is chosen. The chosen reference is then used to weigh the DG frequency and voltage offsets found in its linear droop expressions, so that the less costly DGs produce more power in the steady state. The overall microgrid TGC is thus reduced without violating any power, frequency and voltage limits of the individual DGs. These expectations have been verified through experiments for different microgrid configurations at different loading levels.
- *Section 3.4.2 of Chapter 3* : At times, an exact reference cost-function might not be known to all DGs. For those cases, an approximate quadratic cost-function can be used instead. Results show that the approximation proposed is sufficient to keep the microgrid TGC low, hence demonstrating the insensitivity of the scheme towards parameter variations.
- *Section 3.5 of Chapter 3* : Although the droop schemes discussed earlier can lead to a lower TGC for the considered microgrid, they might not be able to track the cost curve variations accurately, especially when the cost-functions are highly nonlinear with respect to each other or non-quadratic. A cost-

based droop scheme with more accurate cost-function tracking and reactive power sharing is thus proposed in this section, whose goal is again to reduce the TGC of the considered microgrid, but at a better tracking accuracy.

- *Section 3.5.4 of Chapter 3* : At times, users of the proposed droop scheme in *Section 3.5* might request for additional deciding factors to be included. For that, a modification is presented here to demonstrate how the DG ratings can be included for decision making. The obtained TGC is expected to be higher than that of the pure cost-based scheme, but still lower than the basic droop scheme. This is, no doubt, a tradeoff faced if other deciding factors are favored over costs.
- *Section 3.6 of Chapter 3* : Stability of the cost-based droop schemes is discussed when compared with the traditional droop scheme. Possible application of the cost-based droop schemes to low voltage resistive network with secondary control included is also discussed.
- *Section 4.2 of Chapter 4* : Unlike the earlier droop schemes, the linear cost-prioritized droop scheme proposed in this section aims to reduce the microgrid TGC by defining dispatch priorities and new droop coefficients for the DGs based on their respective cost-functions. Unlike the earlier schemes too, the linear scheme proposed here considers the no-load costs of the DGs when prioritizing their power dispatches. Doing so ensures that the costlier DGs are turned off when the load is low, and will only be turned on when the load increases. The costlier DGs are therefore serving as intelligent reserve generators, whose duties are to satisfy the load, and to keep the microgrid TGC lower than the other schemes discussed earlier. The latter is especially true during light load conditions.

- *Section 4.2.2.2 of Chapter 4* : To add more details from the DG cost-functions, the nonlinear cost-prioritized droop scheme is proposed, which although is more accurate, is also more complex to realize. The linear and nonlinear cost-prioritized droop schemes should hence be chosen on a case-by-case basis depending on requirements and scenarios under consideration.
- *Section 4.3 of Chapter 4* : Stability of the cost-prioritized droop schemes is discussed when compared with the traditional droop scheme. An example demonstrating how the cost-prioritized droop schemes can be used with a low voltage resistive network is also given.

1.7.2 Distributed Droop Schemes for Interlinked AC Microgrids

A number of distributed droop schemes have been developed for managing power flows among interlinked ac microgrids. Their effectiveness during different modes of operation (islanded and grid-connected modes) under different load conditions has already been verified through experimental testing. Some details of the schemes are now briefly discussed here to emphasize contributions made in that aspect of research.

- *Section 5.2 of Chapter 5* : Distributed droop scheme for controlling interlinking converters has been developed, which when implemented, enforces the intended active power sharing among the inter-tied microgrids. The intention demanded here is to minimize the number of interlinking converters in operation, and hence their accompanied losses. Reactive power support, where necessary, can also be provided by the interlinking converters without stressing any of the DGs and their interfaced converters. The proposed scheme works fine with or without any of the inter-tied microgrids connected to the utility grid (infinite bus). It is

thus relatively robust with no modification needed for different modes of inter-tying.

- *Section 6.2 of Chapter 6* : Converters interfacing sources and inter-tying microgrids should be viewed as different entities, even though they might be topologically similar. Their assigned generation responsibilities should hence be different. For the proposed scheme, that translates to the source converters concentrating more on active power harnessing, while the interlinking converters focus more on meeting the load reactive demand. Where necessary, the interlinking converters can also be programmed to transfer active power from an under-loaded microgrid to an overloaded microgrid. The latter can then supply loads in excess of its rated capacity, which otherwise, cannot be done by a single microgrid alone. Performances of the scheme have already been verified through experiments for different load conditions seen by the interlinked microgrids.
- *Section 6.3 of Chapter 6* : A limitation faced by the earlier interlinking droop schemes can be explained by referring to the simple example of two microgrids tied together. If both microgrids are under-loaded, and one of the microgrids is tied to the utility grid, the schemes mentioned above will result in both microgrids generating enough for their own light loads. Their efficiencies are hence low with no active power transferred to the utility grid. Although the system will still operate, its performances are far from optimized, which in Section 6.3, are resolved by including active power export features during light load conditions to the interlinking droop characteristics. With such inclusion, active power will be exported to the utility grid, even if both microgrids in the quoted example are experiencing light load conditions. Efficiencies of the

microgrids are thus improved with their generation intensities now being higher than those demanded by their respective loads.

1.8 Organization of the Thesis

Chapter 1 gives an introduction of distributed generation, microgrids and concepts linked to the inter-tying of multiple microgrids. The problem statements and proposed research themes for standalone and interlinked microgrids are also explained, followed by a brief review of existing power sharing schemes for standalone microgrids. The guiding research objectives, original contributions made and chapter layout are also described in the chapter.

Chapter 2 reinforces Chapter 1 by providing a more thorough review of control architectures found with different types of DGs in a microgrid. It includes a description of the basic droop scheme and its implementation with DGs interfaced by converters or of the internal combustion engine (ICE) type. Variants of the basic droop scheme and related stability analysis for a standalone microgrid are also reviewed, after highlighting concerns associated with them. The desired control features and requirements for a standalone microgrid are subsequently identified, before proceeding to the review of existing control methods for interlinked microgrids and the identification of suitable interlinking requirements.

Based on the understanding gained from Chapter 2, **Chapter 3** presents four different distributed droop schemes capable of reducing the total generation cost of a standalone microgrid. To do that, active and reactive power generation cost characteristics of the DGs are developed based on quadratic functions already identified in the literature. The identified characteristics are subsequently used to develop four improved droop

methodologies, whose control decisions are made based on the DG operating characteristics rather than ratings alone. For each scheme, experimental results showing the intended power sharing and accompanied cost saving are given for different microgrid configurations and load conditions. These results are further reinforced by a stability analysis performed on the cost-based droop schemes.

Chapter 4 continues with the findings discussed in Chapter 3 by presenting two cost-prioritized droop schemes, which can again give rise to a reduced total generation cost for the considered standalone microgrid. The first scheme is based on linear droop expressions, while the second is based on nonlinear droop curves. Comparatively, the first scheme is thus simpler, while the second scheme can capture more cost details around the mid loading level. Both methods are explained in details with their experimental results presented for validation. Discussion about their stability issues and application to low voltage resistive network are also presented before concluding the chapter.

Chapter 5 then diverts the focus to interlinked ac microgrids with a method presented for managing their interlinking converters. The proposed method is explained and tested with an example system consisting of two interlinked microgrids. Results obtained from the testing under different load conditions are provided for reinforcing the theories discussed.

Chapter 6 furthers the findings discussed in Chapter 5 by presenting two variants of the interlinking droop scheme. The concept of adaptive capacity tuning and its mathematical models are introduced for both variants, before testing them in

experiments for different load conditions. The results obtained are analyzed and found to agree with expectations.

Chapter 7 finally concludes the research work performed, followed by providing a few recommendations for future research.

Chapter 2

Review and Identification of Distributed Control Requirements for Standalone and Interlinked Microgrids

2.1 Introduction

This chapter reviews the traditional droop principles and issues relevant to both standalone and interlinked ac microgrids. From the review, desired control requirements have been identified, from which improved schemes have been proposed from Chapter 3 onwards for both standalone and interlinked ac microgrids.

2.2 Review of Droop Scheme for Standalone Microgrids

2.2.1 Basic Power Flow Control

Power flow control of generation source is achieved using simplified power equations, which are explained in this section. Taking an example of two nodes network shown in Fig. 2-1(a) and (b), the power flow relation between node “A” and node “B” can be derived from the apparent power equation given by (2-1),

$$\bar{S} = \bar{V}_A \bar{I}_A^* = P + jQ$$
$$P + jQ = V_A \frac{(V_A - V_B e^{j\delta})}{Z e^{-j\theta}} = \frac{V_A^2}{Z} e^{j\theta} - \frac{V_A V_B e^{j(\theta+\delta)}}{Z} \quad (2-1)$$

(a)

(b)

Fig. 2-1. (a) Example of two node based network and (b) voltage phasor diagram

Subsequently, apparent power equation (2-1) can be separated into its real (active power) and imaginary (reactive power) parts, as given below.

$$P = \frac{V_A^2}{Z} \cos \theta - \frac{V_A V_B}{Z} \cos(\theta + \delta) \quad (2-2)$$

$$Q = \frac{V_A^2}{Z} \sin \theta - \frac{V_A V_B}{Z} \sin(\theta + \delta) \quad (2-3)$$

After substituting “ $Z \cos \theta = R_l$ ” and “ $Z \sin \theta = X_l$ ” in above equations, the active and reactive power equations can be expressed by (2-4) and (2-5).

$$P = \frac{V_A}{R_l^2 + X_l^2} [R_l(V_A - V_B \cos \delta) + X_l V_B \sin \delta] \quad (2-4)$$

$$Q = \frac{V_A}{R_l^2 + X_l^2} [-R_l V_B \sin \delta + X_l(V_A - V_B \cos \delta)] \quad (2-5)$$

Assuming that the line between nodes “A” (phasor voltage notated as $V_A \angle \delta_A$) and node “B” (phasor voltage notated as $V_B \angle \delta_B$) is predominantly reactive ($R_l \ll X_l$), the equations (2-4) and (2-5) can be further simplified as in (2-6) and (2-7).

$$P = \frac{V_A V_B \sin(\delta_A - \delta_B)}{X_l} ; \Rightarrow P \propto (\delta_A - \delta_B) \quad (2-6)$$

$$Q = \frac{V_A^2 - V_A V_B \cos(\delta_A - \delta_B)}{X_l} ; \Rightarrow Q \propto (V_A - V_B) \quad (2-7)$$

Since the phase difference between the two nodes $(\delta_A - \delta_B)$ is usually small, the sine and cosine terms in (2-6) and (2-7) will tend towards $(\delta_A - \delta_B)$ and 1, respectively. Upon substituting these approximations, (2-6) and (2-7) spell that active and reactive powers can linearly be regulated by tuning the phase difference and voltage magnitude, respectively. The former can in turn be changed by varying frequency.

2.2.2 Traditional Droop Scheme

The droop scheme has been widely used for power sharing in conventional power stations [61], [62], [65], [66], and then the same concept has been extended to UPS [68]-[74] and DGs in microgrids. The purpose however remains the same, to achieve autonomous power sharing among the different units/DGs [63]. To explain its basic power sharing principle, the following two assumptions are made for simplification.

- DG feeders or lines are predominantly reactive
- Voltage drops across DG feeders or lines are the equal

An illustration of the converged basic droop scheme for active and reactive power is shown in Fig. 2-2 (a) and (b). In Fig, the active and reactive power droop lines are plotted using two linear expressions given by (2-8) and (2-9), where x , f , V , $\{P$ and $Q\}$ and $\{max$ and $min\}$ represent DG unit number, frequency, terminal voltage, active, and reactive power generations, and their corresponding maximum and minimum values, respectively.

Fig. 2-2. Traditional (a) active power vs. frequency droop (b) reactive power vs. voltage droop

$$f_x = f_{max} - m_x P_x ; \quad m_x = \frac{f_{max} - f_{min}}{P_{x,max}} \quad (2-8)$$

$$V_x = V_{max} - n_x Q_x ; \quad n_x = \frac{V_{max} - V_{min}}{Q_{x,max}} \quad (2-9)$$

Also included in the two expressions are the active " m_x " and reactive " n_x " droop coefficients, which no doubt are just the gradients of the two droop lines. Implementation of the two droop lines would generally involve measuring the DG terminal voltages and currents for computing its active and reactive power generations. The obtained powers P_x and Q_x can then be substituted into (2-8) and (2-9) to obtain the frequency f_x and voltage V_x references for forming a set of three-phase sinusoidal commands.

The voltage and frequency operating ranges (*min* and *max* values) chosen for the droop scheme when applied to a microgrid should also be noted/set to base on the loads under consideration and the tradeoff that they can tolerate. To be more precise with the tradeoff, wide voltage and frequency ranges are noted to provide better power sharing performance but at the expense of poorer voltage and frequency regulation (hence stability), and vice versa. It is therefore important to consider all factors before deciding on the appropriate parameter ranges to use.

The common objective of droop scheme is to maintain proportional power sharing based on DG ratings [63]. For (2-8) and (2-9), it would mean setting the droop coefficients according to (2-10) and (2-11).

$$m_1 P_{1,max} = m_2 P_{2,max} = \dots = m_x P_{x,max} = \dots = f_{max} - f_{min} \quad (2-10)$$

$$n_1 Q_{1,max} = n_2 Q_{2,max} = \dots = n_x Q_{x,max} = \dots = V_{max} - V_{min} \quad (2-11)$$

To demonstrate the effectiveness of (2-8) and (2-9), a simple microgrid with three DGs is considered, which in the steady state, will share a single common network frequency f ($= f_1 = f_2 = \dots = f_x$). Substituting " f " into (2-8) leads to (2-12), which would force the higher rated DG to produce more active power in order to satisfy the equality. The same principle can be applied to reactive power sharing, whose resulting expression is shown in (2-13). In (2-13), the equality shown is only approximate due to the practical fact that terminal voltages of DGs will never be exactly equal in the steady state. This imperfection has led to many variations discussed in subsequent section of this chapter, whose sole objective is to improve on reactive power sharing based again on ratings.

$$\frac{P_1}{P_{1,max}} = \frac{P_2}{P_{2,max}} = \dots = \frac{P_x}{P_{x,max}} \quad (2-12)$$

$$\frac{Q_1}{Q_{1,max}} \approx \frac{Q_2}{Q_{2,max}} \approx \dots \approx \frac{Q_x}{Q_{x,max}} \quad (2-13)$$

2.2.3 Implementation of Droop Scheme in DGs

Before discussing the implementation of droop scheme, different types of DGs used for microgrid application are briefly reviewed. Generally, DGs can be classified into two categories notated as inverter-interfaced and non-inverter interfaced (or direct interfaced) type.

2.2.3.1 Non-Inverter Interfaced DGs

For microgrid application, Synchronous Generator (SG) is the most commonly used non-inverter interfaced type of DG with inherited droop characteristics [65]-[67]. Synchronous generator voltage angle can be controlled by its torque and hence its active power can be regulated by controlling the phase angle (frequency) at the generator terminal. Similarly, the voltage of synchronous generator can be controlled through the exciter to regulate the reactive power of synchronous generator. Fig. 2-3 shows the generator simplified schematic of synchronous generator for voltage and angle control to regulate the active and reactive power.

Fig. 2-3. Synchronous generator voltage and frequency control

2.2.3.2 Inverter Interfaced DGs

All the generation sources that inherently produce dc or variable voltage require power electronic converters to regulate their output power voltage and frequency for interfacing with the power network. From microgrid application point of view, these sources can be classified into two main categories notated as grid-following and grid-forming types.

The energy sources such as fuel cell, storage technologies that can maintain output constant dc link voltage are usually interfaced through voltage source inverter (VSI).

This type of DGs can form a grid, which means, in principle they can provide voltage reference to a standalone microgrid. The grid-forming DGs have black-start capability, their active and reactive power output can be controlled. The later capability for active and reactive power control makes these DGs dispatchable. The typical diagram representing the grid-forming type of DG is shown in Fig. 2-4.

Another category of microgrid DG consists of intermittent energy sources such as solar PV and Wind Turbines Generator (WTG) that inherently produce variable dc or ac voltage. These DGs with intermittent energy sources are usually non-dispatchable, and are hence classified as the grid-following type. To achieve black-start and dispatch capabilities, the grid-following DGs can be transformed into grid-forming dispatchable DGs by adding the energy storage technologies coupled at their DC link, as shown in Fig. 2-5.

Fig. 2-4. Typical grid-forming DGs

Fig. 2-5. Current generation sources with storage model as a grid-forming DGs

Being dispatchable sources now with energy storage, the droop scheme can be implemented in the dispatchable DGs inverter/converter, the detail of which is discussed in the following section.

2.2.3.3 Control Schematic for DG Inverter

The typical control schematic for DG inverter is given in Fig. 2-6, where it shows different sub-control blocks notated as power computation block, droop controller, voltage and current controller and PWM pattern synthesizing block, other than the DQ de-coupler, ABC to DQ and DQ to ABC conversion blocks. This is the most commonly used basic control scheme for droop implementation in DG, however, practically scheme needs to be tailored for the droop scheme variant and the desired control features.

Fig. 2-6. DGs inverter typical control schematic with droop control

Power Computation

First control block in Fig. 2-6 schematic is the power computation block, where real-time active and reactive power values are calculated from three phase instantaneous currents (i_{abc}) and voltages (v_{abc}). The fundamental amplitudes of the positive sequences voltage (V) and current (I) are computed using PLL from three phase instantaneous voltages and currents. Subsequently, the active and reactive power can be calculated using (2-14) and (2-15), where $\Delta\phi$ is the phase difference between voltage and current [75].

$$P = \frac{3}{2}VI \cos \Delta\phi \quad (2-14)$$

$$Q = \frac{3}{2}VI \sin \Delta\phi \quad (2-15)$$

Droop Controller

The droop controller shown in the schematic is based on droop equation (2-8) and (2-9), where P and Q are the input from power computation block and the f_{max} , f_{min} , V_{max} , V_{min} , m and n are the constant parameters for the DGs. The output of droop controller block is the reference voltage (V_x) and frequency (f_x), which are then merged together to form sinusoidal voltage reference.

Dual Loop Voltage and Current Controllers

The sinusoidal voltage references generated from the droop controller can be tracked by the current and voltage controllers shown Fig. 2-6. Over the last few decades many types of controllers have been surfaced including hysteresis controllers, linear PI regulators and predictive dead-beat regulators, and PR controllers. These controllers can be further classified into different types and each of this controller exhibit different performance in synchronous and stationary reference frames [76]-[82]. Practically,

among all, *PI* controller with synchronous reference frame is the most commonly used in many engineering applications including DGs VSI control.

The above droop equations can be implemented based on the control block arrangement shown in Fig. 2-6. The only difference noted with the figure is the regulation of grid currents i_a , i_b and i_c , instead of those flowing through the filter inductors L_f . The latter are usually used but would require three additional current sensors. For simplicity, the grid currents can be measured, and subtracted by an estimate of the filter capacitor currents $i_{cf,abc}$ in (2-16) to get the estimated filter inductor currents.

$$i_{cf,abc} = sC_f v_{abc} / (1 + s/\omega_{cut}) \quad (2-16)$$

where v_{abc} represents the source terminal voltages. Also included in (2-16) is a low-pass filter with cutoff frequency of ω_{cut} for reducing noise amplification.

DQ Decoupling

The mathematical model derived in equation (2-17) and (2-18) for the voltage source inverter (*VSI*) shows cross coupling between *DQ* components due to the filter impedance. Decoupling is therefore necessary for independent control of DG frequency (active power) and voltage (reactive power). Among the reported decoupling techniques, it can either be achieved using a feed-forward or feed-back de-coupler [83]-[88]. The *DQ* decoupling block is therefore added in the control schematic shown in Fig. 2-6.

$$V_{d_ref} = K_{pi}(i_d^* - i_d) + K_{ii} \int (i_d^* - i_d) dt - \omega^* L_f i_q + v_{od} \quad (2-17)$$

$$V_{q_ref} = K_{pi}(i_q^* - i_q) + K_{ii} \int (i_q^* - i_q) dt + \omega^* L_f i_d + v_{oq} \quad (2-18)$$

Modulation Signal Synthesizing

The last control block is the Pulse Width Modulation (PWM) signal synthesizing. Among all, Sinusoidal PWM (SPWM) and Space-Vector PWM (SVPWM) are the commonly used techniques for switching pattern synthesizing. The SPWM switching technique with *PI* controllers eliminates steady state error and has fast transient response when applied to synchronous frame (dc) values. The drawback of this scheme is the cross-coupling due to filter inductors (discussed in above paragraph) and frame transformation complexity. The SPWM control at high switching frequency can eliminate lower order harmonics and generates pure sinusoidal output [12] but on the other hand higher switching frequency cause higher losses. The PWM switching pattern is therefore used to control the inverter IGBTs through gate drive.

The basic control schematic for droop implementation in inverter interfaced DG has been reviewed in above section; however, this basic scheme needs to be tailored for the considered droop variant. Apart from the variation, additional control features are required for DG operation in microgrid and hence need to be incorporated in the control schematic. These may include rating limits, synchronization, dc link voltage control and details of these control features are discussed in subsequent chapters.

2.2.4 Review of Existing Droop Variants for Microgrid Applications

2.2.4.1 Problem Associated with Traditional Droop Scheme

Despite many advantages, the most recent research shows the technical difficulty of implementing the traditional droop scheme in the low voltage microgrid systems, as summarized below,

- Power sharing performance of traditional droop scheme is affected when applied to LV microgrids where the network is predominantly resistive rather than inductive as assumed while deriving basic power flow equations (2-6) and (2-7).
- Reactive power sharing performance is affected due to voltage mismatch at DG terminals. The voltage difference at the DG terminals could be due to the different voltage drop in the DG feeders.

To address these issues, many variations have since been extended from the basic traditional droop scheme, whose common objective is to maintain proportional power sharing based on the DG ratings. Different variants of the traditional droop scheme are reviewed in the following section.

Transformation Based Droop Scheme

In [89], author proposed to apply orthogonal transformation matrix (T) to compensate the feeder line impedance. The modified decoupled active power (P') and reactive power (Q') can then be computed using (2-19). These modified active and reactive power can be controlled independently using (2-20) and (2-21), where active power (P') is proportional to angle (δ) and reactive power (Q') is proportional to voltage difference between sending (V_A) and receiving (V_B) nodes in the network.

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = T \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \frac{X}{Z} & -\frac{R}{Z} \\ \frac{R}{Z} & \frac{X}{Z} \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \quad (2-19)$$

$$\sin\sigma = \frac{ZP'}{V_A V_B} \quad (2-20)$$

$$V_A - V_B \cos\sigma = \frac{ZQ'}{V_A} \quad (2-21)$$

In the proposed transformation based decoupling method, it is necessary to know the line impedance angle, in other words R/X , to derive the transformation matrix $[T]$.

Above mentioned transformation based droop method was further modified where the active and reactive currents based scheme is proposed, rewritten as equation (2-22). The current based scheme reported to have better performance under faults or transients conditions when network voltage is low. Again, in the current based droop scheme equations (2-23) and (2-24), the arctangent of line needs to be known or assumed. The accuracy of power sharing in this scheme depends on the guess made for R/X value.

$$\begin{bmatrix} Ia' \\ Ir' \end{bmatrix} = T \begin{bmatrix} Ia \\ Ir \end{bmatrix} \quad (2-22)$$

$$f - f_o = -ka(Ia' - Ia, o') \quad (2-23)$$

$$Va - Vo = -kr(Ir' - Ir, o') \quad (2-24)$$

Virtual Impedance Based Droop Schemes

The number of droop variants has been surfaced with the concept of virtual voltage source, virtual resistance and virtual impedance.

The virtual impedance voltage source approach was proposed for the voltage and frequency droop controller to imitate the behavior of resistance without compromising losses in real system [89]. In this approach, the voltage droop is achieved as a result of the difference between instantaneous values of virtual source voltage and actual grid voltage, across the series connection of the (virtual) resistance and inductance. Similarly, the frequency droop is realized as a result of phase angle difference between the virtual source terminal and the fundamental grid voltage component. Compared with the traditional droop control method, this approach achieves more efficient control of frequency and voltage. Other advantages of this scheme include harmonics reduction and better control during short circuit due to the proposed modified current control scheme discussed in above paragraph.

A few other droop schemes based on virtual output resistance and impedance have been proposed with common objective to decouple the active and reactive power control [73],[74],[90]-[96]. The concept of virtual impedance application is illustrated through Fig. 2-7, where virtual impedance is shown in the control feedback unlike in the real network. Virtually applied impedance decouples the control between active and reactive power in low voltage microgrids without causing real losses in the power stage. A proper design of output virtual impedance can also reduce impact of line-impedance unbalance.

Fig. 2-7. Virtual output impedance loop

Adaptive Droop Schemes

Several adaptive droop schemes have been proposed. In [97] author proposed adaptive droop scheme where the droop parameters can be adjusted based on estimated grid parameters (impedance magnitude, phase angle, voltage and frequency). These grid parameters are estimated based on voltage and current variation at DG Point of Common Coupling (PCC) due to the change in active and reactive power output of DG. Adaptive tuning of droop parameter can decouple the active and reactive power control. The accuracy of this scheme depends on the measurement accuracy of voltage and frequency at PCC.

Another adaptive droop controller was presented in [98] where the droop gains are selected to improve the voltage and frequency regulation and stability of the system. Based on proposed scheme, the transient gains can be adaptively tuned to damp the oscillatory modes under various operating conditions.

Apart from above mentioned schemes, input–output linearization control techniques [68], $Q-V$ dot droop controller [99], additional control signal injection method [100], stability constrained droop scheme [101]-[103] have been proposed, mainly focused to achieve decoupled and proportional power sharing among DGs in LV microgrid.

Feeder Impedance Compensation Schemes

So far, several droop schemes have been reported for feeder impedance imbalance compensation [95], [96], [100]-[106]. In almost all of these schemes the main objective is to compensate the feeder line impedance imbalance to achieve accurate and proportional reactive power sharing among DGs based on their power ratings.

In summary, extensive research has already been carried out to address the issue of coupling in active and reactive power control due to low voltage resistive network and inaccuracy in reactive power sharing due to feeder line imbalances. Any of the reviewed droop scheme can be applied while implementing droop scheme in microgrids; therefore these issues will not be discussed further, rather, upcoming sections are focused on the proposed characteristics or cost based droop scheme for standalone microgrid.

In the view of existing research in droop schemes, following section highlights some of the general control requirements and features for standalone microgrid, based on which cost-based droop schemes are being proposed.

2.2.4.2 Stability of Microgrids

Like most systems, microgrid stability is studied by applying modern control theories with the resulting system modelled by a set of differential state-space equations. The desired state variables can then be evaluated by forming a finite matrix for representing the system, from which the necessary Eigenvalues can be computed [107]. This approach has been used extensively for studying the dynamics and small signal stability of microgrids from various aspects. The main purpose is to establish the relevant stability theories for droop-controlled converters and microgrids, so that the proper converter design, components, control gains and network parameters can be chosen.

In [108-111], small-signal models for droop-controlled converters and microgrids have been developed with the aim being to study the effect of line impedance on microgrid stability. The study shows that lower line impedance leads to instability, and vice versa. In addition, it has been found that load and network impedances have very small impact on the system stability. On the other hand, if the equivalent impedance between DGs is very small, it may lead to instability. It is hence important to consider the possible effect of line impedance during the stability study and microgrid design. In [108], the impact of filter cut-off frequency has been studied, whose results shows that the system response becomes slow and under-damped when the cut-off frequency is set too low. On the other hand, it fastens as the filter cut-off frequency increases without causing instability. This may be due to the ignoring of high frequency ripple in the stability model.

Another aspect studied for the droop-controlled converter is the impact of droop gains has on the microgrid stability [109], [110], [112]-[114]. The common finding concluded is the pushing of microgrid to its instable region as the droop gains increase. The droop

gains should however not be overly small, since power sharing will be greatly compromised even if the system is stable. A trade-off must therefore be determined for the considered microgrid. Alternatively, modified droop schemes with better stability margins can be used. For example, an adaptive droop scheme has been proposed in [98] for improving the dynamic performance and stability of microgrid without affecting the static droop gains. Another scheme that uses an additional communication link has been proposed in [115], where the critical factor considered is the effect introduced by communication delay. Small communication delay ensures stability, but not long delay at high droop gains. In [101], a supplementary loop has been proposed for keeping the system stable even with high droop gains. The resulting system thus shares power better, while preserving its stability.

It is therefore presently clear that to improve the system stability, the droop gains chosen must be small, while yet not compromising power sharing accuracy. If higher gains are needed, alternative modifications must be introduced to the basic droop scheme like those reviewed above.

2.3 Identified Control Requirements for Standalone Microgrids

In almost all the droop schemes reviewed in above section, the common objective is to achieve accurate and proportional active and reactive power sharing based on DGs ratings. The principle of proportional power sharing works fine with the usually similar DGs in microgrid or microgrid with economic dispatch through central management system, but might not suit well with DGs having different characteristics and without central management system in place. To address these concerns with the existing droop

schemes, some of the general control requirements and possible constraints have been identified in the following points, which are then followed as guidelines for developing the cost-based droop schemes.

- *Consideration of DG Characteristics:* Unlike traditional droop scheme, the droop scheme shall consider the DGs operating characteristics such operating costs, environmental impact or even life cycle. Thus the droop scheme shall be able to tune their droop characteristics to achieve one or more than one of the following objectives,
 - Reduce the overall power generation cost in microgrid
 - Reduce the environmental impact
- *Generic:* The droop scheme with DGs characteristics considered should be generic enough so that it can be applied to a microgrid comprising of different rating or type of DGs.
- *Operating Limits:* DGs in a microgrid should operate within defined power, voltage and frequency ratings
- *Autonomous Control:* The control scheme shall be fully autonomous and independent of communication links among DGs.
- *Flexibility:* Droop scheme inherited control flexibility features shall be retained. These features may include addition or replacement of DGs in a microgrid.
- *Stability:* Unquestionably, the overall microgrid stability must be ensured after applying the designed droop schemes.

In a view of above mentioned desired features and constraints, a number of new droop schemes have been developed; the detail of those schemes is given in Chapter 3 and Chapter 4.

2.4 Review of Existing Control for Interlinked AC Microgrids

The droop schemes reviewed in above section for a single microgrid are not directly applicable to interlinking converters tying two or more microgrids together, which subsequently prompts some initial intertying efforts like those found in [116-118].

Reference [116], in particular, discusses the tying of a microgrid to the utility grid, which in principle, can be viewed as a second stronger microgrid. Two different modes of operation are applied to the grids with the first having the microgrid droop-controlled and the utility grid regulated at a constant contractual power. Their roles are reversed in the second mode with the microgrid operating at its full-rated power and the utility grid behaving like a drooped source through the control of its ac-dc-ac converter. Although this studied system might appear more complex than a single ac microgrid, its underlying droop scheme is conceptually unchanged. This can be explained by noting that at any instant, only one grid is droop-controlled, while the other behaves like a constant power source. Loading in the utility grid is also not considered, while deciding on the necessary control actions. In other words, the utility grid has been treated as an infinite bus, whose presence will not affect the droop scheme applied to the single accompanied ac microgrid.

A second example related to intertied microgrids can be found in [117], [118], where two or more single-phase microgrids are tied together. Various power converter topologies are explored for microgrid intertying application. Among all, back-to-back converter topology is reported to have better performance. The focus in these references is to improve transient response and minimize dc-link power pulsation at the converter intertying two single-phase microgrids.

These objectives are no doubt important given that they have been mentioned in nearly all power electronic applications. They are however not directly related to the intertying of microgrids. Rather, power flow management among the microgrids might be an other relevant topic, whose implementation would usually involve the interlinking power converters and DGs operating autonomously. Some general control requirements and features are discussed in the following section for interlinked ac microgrids.

2.5 Identified Control Requirements for Interlinked AC Microgrids

Although the power networks or microgrids intertying concept is not new, application of distributed control scheme to interlinked microgrids can be more challenging because of a number of related operating issues. To develop an appropriate scheme for power management, the desired control features and requirement thus need to be identified. Preferably, the implemented control and management schemes should be autonomous without demanding for fast communication links. They should constantly monitor the local active, reactive and apparent power ratings of the inter-tied ac microgrids, before making a sound control decision. The key desired features and control requirements that two interlinked ac microgrid should be able to meet for power flow management among them are:

Reserve Sharing: Interlinked microgrids shall be able to transfer active power from an under-loaded microgrid to an overloaded microgrid. Reserve sharing is thus affected without introducing extra backup generators.

Reactive power and voltage support: The microgrids interlinking converters should be able to provide reactive power support to microgrids, specially under heavy loading

condition, during which microgrid DG has been stressed out. Reactive power supply control for both side of back-to-back interlinking converter shall be independent.

Efficient Operation: In order to operate the interlinking inverters efficiently and to minimize the transfer losses, the interlinking inverter shall stop operation when interlinked microgrids are under same loading conditions. Thus transfer shall only happen when either of one microgrids is heavy loaded and another microgrid has available reserve to transfer.

DC link/Synchronization: Apart from the listed power management requirements, the dc link voltage of back-to-back interlinking converter shall be maintained within permissible limit, microgrid interlinking converter shall be able to automatically island and re-synchronize as and when needed, as determined by proposed scheme.

Above given points summaries the key requirements for power management among interlinked microgrids, however, more specific and detailed features are discussed in subsequent Chapter 5 and Chapter 6.

2.6 Conclusions

The traditional droop basic working principle and implementation details are reviewed for DG application in a microgrid. The issues associated with traditional droop schemes such as coupling of active and reactive power control due to predominantly resistive network and reactive power sharing inaccuracy due to feeder impedance are highlighted. To achieve the accurate proportional power sharing, different version of droop schemes surfaced so far are reviewed for microgrid applications. In the last section, the desired control features and requirements are identified for standalone

microgrid. Similarly, the existing control schemes for interlinked ac microgrids are reviewed and desired control requirements are summarized for interlinked microgrids.

The literature review and findings from this chapter are used as a guideline for the development and implementation of new proposed droop schemes for standalone and interlinked ac microgrids. The details of those schemes are given from Chapter 3 to Chapter 6.

Chapter 3

Cost-Based Droop Schemes for Standalone Microgrids

3.1 Introduction

This chapter presents concepts, methodologies and experimental results obtained from four cost-based droop schemes proposed for standalone microgrids. Power generation cost characteristics for different types of DGs are reviewed first, before mathematical models and the basic cost-based principles are explained. Description of the experimental system and results then follows, before the chapter is concluded by emphasizing the contributions made.

3.2 The Concept of Characteristics or Cost-Based Droop Scheme

In standalone microgrid where centralized management and communication links are not viable, droop control has been the preferred scheme for DGs. At present, although many droop variations have surfaced, they mainly focus on achieving proportional power sharing based on the DG kVA ratings, as reviewed in Chapter 2. This objective is no doubt fine if the DGs are of the same type like in the earlier control of parallel

synchronous generators [61],[62],[65]-[67] and uninterruptible power supplies [68]-[72].

It is however usually not the case for microgrids, where different types of DGs having different cost and emission characteristics usually exist. Proportional power sharing based on ratings alone might therefore not be comprehensive for microgrids. Other factors like costs, efficiencies, pricing schedules and emission penalties should be considered like in most centralized systems, where power dispatch commands are usually decided from a combination of factors rather than ratings alone. The same thought has however never been tried with droop control for standalone rural or islanded microgrid. To address the concern raised above and the requirements identified in Chapter-2, a number of different droop schemes have been developed to produce power sharing based on minimizing the generation costs or weighted combination of factors for the considered microgrid, rather than ratings alone. In total, six variations of cost-based droop schemes have been recommended, four (4) of which are covered in Chapter 3 and other two schemes are covered in Chapter 4.

The power sharing arrived in the steady state will meet the intended objectives without compromising the simplicity of the droop operating principles. Simplicity of the proposed scheme has been retained even though it includes more terms and higher order cost-functions in its decision making. The results obtained are promising with the following features demonstrated.

- Lower TGC for the considered microgrid
- Overall simplicity preserved, and hence more likely to meet industry requirements
- Defined frequency, voltage and power ranges of each DG not violated

- Plug-and-play flexibility of the DGs is preserved
- Better regulation of microgrid frequency and voltage

The proposed schemes have been verified through experiment with the example objective defined as minimizing the overall operating cost in microgrid.

3.3 Generation Cost-Functions of DGs

The generation cost of DGs may vary widely depending on DG type and capacity. In general, the generation costs of a DG can be divided into two parts, active and reactive powers generation costs. They are respectively notated as $C_{P,x}(P_x)$ and $C_{Q,x}(Q_x)$ in the following sections where their definitions are elaborated.

3.3.1 Active Power Generation Cost for ICE Type of DGs

The active power cost of a DG can include many factors, which for a diesel generator driven by an internal combustion engine or an electromechanical generator driven by a micro-turbine, can be grouped under two main categories. They are respectively named operation cost notated as $C_{P,o,x}(P_x)$, realized by adding the maintenance and variable fuel cost and emission penalty or incentive cost notated as $C_{P,\xi,x}(P_x)$, whose sum gives $C_{P,x}(P_x)$ in (3-1).

$$C_{P,x}(P_x) = C_{P,o,x}(P_x) + C_{P,\xi,x}(P_x)$$

$$C_{P,x}(P_x) = C_{P,o\&m,x}(P_x) + C_{P,fuel,x}(P_x) + C_{P,\xi,x}(P_x) \quad (3-1)$$

In general, the maintenance cost can be represented by a linear function of power (3-2), and the variable fuel and emission related costs of a generator driven by an engine or a turbine can be represented by those second-order quadratic expressions written in (3-3)

[61],[119]-[127] and (3-4) [122]-[127], where, $a_x, b_x, c_x, \alpha_x, \beta_x, \gamma_x, \epsilon_x$ and ρ_x are coefficients characterizing the generator under consideration, and $K_{fuel,x}, K_{emm,x}$ are scaling/conversion factors for converting the fuel and emission levels to their equivalent costs.

$$C_{P,o\&m,x}(P_x) = K_{o\&m,x}P_x \quad (3-2)$$

$$C_{P,fuel,x}(P_x) = K_{fuel,x}(a_x + b_xP_x + c_xP_x^2) \quad (3-3)$$

$$C_{P,\xi,x}(P_x) = K_{emm,x}(\alpha_x + \beta_xP_x + \gamma_xP_x^2 + \epsilon_x \exp(\rho_xP_x)) \quad (3-4)$$

Note that (3-1) does not include capital cost incurred by the considered DG. Although capital cost is important, it is a fixed investment cost committed initially regardless of whether the DG is producing power or not. In other words, it is not affected by the actual power generated, and will hence not affect the slopes of the droop curves. To demonstrate this, a fixed capital cost " C_x " has been summed with other DG costs like in (3-5) for the scheme presented in Section 3.4.

$$C_{P,x}(P_x) = C_x + C_{P,o\&m,x}(P_x) + C_{P,fuel,x}(P_x) + C_{P,\xi,x}(P_x) \quad (3-5)$$

3.3.2 Active Power Generation Cost for Dispatchable Renewable DGs

Being of a different type, cost-functions used with dispatchable green source based DGs such as fuel cell, wind and photovoltaic sources with storage can be derived from their direct operating costs and converter loss-efficiency functions. The direct costs accompanying the green DG can include operation and maintenance (O&M) cost of the solar PV, wind turbine generators, fuel cell [128]-[132], hydrogen fuel cost of the fuel cell [133]-[135], and their green incentives (or negative costs) for lowering emission.

Sum of these direct costs, notated as $C_{P,x,int}(P_x)$, can usually be represented by the linear expression spelled in (3-6),

$$C_{P,int,x}(P_x) = K_{o\&m,x}P_x + K_{fuel,x}P_x \pm K_{emm,x}P_x \quad (3-6)$$

In (3-6), $K_{o\&m,x}$, $K_{fuel,x}$ and $K_{emm,x}$ are constants characterizing the DG under consideration. Equation (3-6) must account converter losses like in (3-7) [136]-[141], whose high values at low load must definitely be included as a cost penalty.

$$P_x = \eta_x(P_x + P_{loss,x}) = \eta_x(P_x + K_{l,x}(v_x + u_xP_x + \omega_xP_x^2)) \quad (3-7)$$

The eventual cost-function $C_{P,x}(P_x)$ for representing a green source based DG can then be derived as (3-8), where η_x , $K_{l,x}$, v_x , u_x and ω_x are again constants for characterizing the considered DGs efficiency/loss function. Equation (3-8) is obviously also a second-order quadratic function, even though it is derived with a different approach.

$$C_{P,x}(P_x) = K_{x,o} \left(P_x + K_{l,x}(v_x + u_xP_x + \omega_xP_x^2) \right), \text{ where} \quad (3-8)$$

$$K_{x,o} = \eta_x(K_{o\&m,x} + K_{fuel,x} \pm K_{emm,x})$$

With (3-1) to (3-8) derived, three illustrative quadratic cost curves can be drawn for the example microgrid shown in Fig. 3-1. The curves can be seen in Fig. 3-2(a), where $C'_{p,1}$ and $C'_{p,2}$ are for representing engine-driven DGs and $C'_{p,3}$ is for the renewable type DG. Note that these curves are plotted as $C'_{p,x}(P_x)$ versus P'_x , whose definition is given by (3-9).

$$C'_{P,x}(P_x) = \frac{C_{P,x}(P_x)}{P_{x,max}} \text{ and } P'_x = \frac{P_x}{P_{x,max}} \quad (3-9)$$

As mentioned earlier, subscript “max” has been added to notate the maximum power that DG x can produce. The division by $P_{x,max}$ is viewed as necessary to prevent the DG

ratings from distorting the cost consideration, hence leading to a wrong conclusion (e.g. DG 1 and DG 2 supplying a load is definitely not cheaper than DG 3 supplying the same load alone, if both rating and cost of DG 3 are doubled than those of DG 1 or DG 2 considered alone).

Fig. 3-1. Example microgrid with three DGs.

Fig. 3-2. Illustration of microgrid DGs generation cost curves (a) $C'_{P,x}(P_x)$ and (b) $C''_{P,x}(P_x)$.

From the plotted curves, the relationship observed from Fig. 3-2(a) can obviously be written as $C'_{P,1} > C'_{P,2} > C'_{P,3}$ for all active power values indicated. It should however be noted that the three curves include their respective no-load (NL) costs at zero active power ($P_x = P'_x = 0$). These costs are fixed expenses paid so long as the DG is ON, and should hence be removed from consideration since they are not influenced by the actual active powers generated by the respective DGs. The modified cost curves can hence be expressed as (3-10), whose graphical plot is shown in Fig. 3-2(b).

$$C''_{P,x}(P_x) = C'_{P,x}(P_x) - C'_{P,x}(P_x = 0) \quad (3-10)$$

3.3.3 Reactive Power Generation Cost for DGs

Other than active power, DGs tied to the microgrid are required to produce reactive power. DGs must hence be designed with the appropriate kVA capacities needed to manage the individual reactive power requests and active power losses accompanying them [142].

Unlike active power, reactive power generation ideally consumes no fuel or energy, and should hence have zero cost. In practice, this is however not true since reactive power generation will definitely lead to active power loss even though the loss value is usually much smaller than the actual active power generated for utilization [143]. The resulting loss value can then be converted to a cost component for reactive power generation. Another cost component can be argued as the opportunity cost incurred by reactive power generation, which otherwise can be used for active power generation [143-144]. In other words, with a demanded reactive power, the active power produced must be reduced if the source rating is fixed ($P_x = \sqrt{S_{x,max}^2 - Q_x^2}$). Both cost components of reactive power generation can eventually be represented by scaled-down quadratic

functions since they are directly or indirectly related to very small active power generation, even though mainly as losses.

No doubt, these reactive power costs vary with the DG types, but in general, they are usually very small. This small percentage will approximately be cancelled when divided by the individual DG maximum reactive power $Q_{x,max}$ (analogous to (3-9)). For the “reference-cost based droop scheme” detailed in Section 3.4, simplified approach is adopted, where reactive power sharing is set analogous to active power, represented by (3-11).

$$C''_{Q,x}(Q_x) \approx C''_{P,x}(P_x) \quad (3-11)$$

However, it is not the strict requirement to set reactive power sharing analogous to active power, instead reactive power sharing can be based on reactive power cost-functions developed for the DGs. The reactive power sharing based on reactive power cost-functions has been tried in the droop scheme given in next Section 3.5, where it is verified that absolute value of reactive power generation cost is marginally small and thus the absolute saving achieved is less too.

More detail on the reactive power cost-function is given in section. 3.5.1.2.

3.3.4 Total Generation Costs of Overall Microgrid

The Total Generation Cost $TGC(P_x, Q_x)$ of the microgrid can then be written as (3-12), where it has been further simplified to $TGC(P_x)$ when the reactive power costs are comparably smaller, and hence can be ignored. Ideally, (3-12) should be reduced for economic reasons, which certainly, is achieved through the proposed methodology.

$$TGC(P_x, Q_x) = \sum (C_{P,x}(P_x) + C''_{Q,x}(Q_x) \times Q_{x,max}) \approx \sum (C_{P,x}(P_x)) = TGC(P_x) \quad (3-12)$$

3.4 Reference Cost-Function Based Droop Scheme

The cost-functions developed in above sections are used to illustrate the methodology for the cost-based droop schemes detailed in the following section.

3.4.1 Methodology

The traditional basic droop scheme reviewed in Chapter 2 is based on the two linear expressions re-written in (3-13) and (3-14) for easy reference, where x , f , V , $\{P$ and $Q\}$, and $\{max$ and $min\}$ are the DG unit number, frequency, terminal voltage, active and reactive power generations, and their corresponding maximum and minimum values, respectively.

$$f_x^* = f_{max} + m_x P_x ; \quad m_x = \frac{f_{min} - f_{max}}{P_{x,max}} \quad (3-13)$$

$$V_x^* = V_{max} + n_x Q_x ; \quad n_x = \frac{V_{min} - V_{max}}{Q_{x,max}} \quad (3-14)$$

From Fig. 3-2(b), it is clear that all three cost curves (and most others in practice) roughly follow a quadratic function. Modification to the basic droop scheme to account for the DG generation costs $C_{P,x}''(P_x)$ can therefore be based on a defined reference quadratic function $C_{ref}''(P_y)$, where subscript y has been introduced for representing the unit number of the DG chosen as the reference. In this scheme, the reference is chosen as the cost curve of the most expensive existing DG or future DG planned for expansion. In Fig. 3-2 (b), the most expensive DG is DG 1, which is hence chosen as the reference quadratic function ($C_{ref}''(P_y) = C_{P,1}''(P_1)$). This is however not a strict requirement, meaning quadratic functions from other DGs can also be chosen with only a slight difference introduced to the scaling factors of the final droop expressions (detail discussed in Section 3.4.2). It will not affect the underlying operating principles.

3.4.1.1 Active Power

The chosen reference and its peak value at maximum power ($C''_{ref,max} = C''_{ref}(P_{y,max})$) can then be used to write the frequency offset $\Delta f_{x,off}$ expression given in (3-15), where a scaling constant $K_{f,x}$ has been introduced. The reason for including $K_{f,x}$ will be mentioned after introducing the necessary active droop expression for the proposed droop scheme. The offset computed with (3-15) can then be added to basic droop equation (3-13) to arrive at the proposed active droop expression in (3-16).

$$\Delta f_{x,off} = \frac{C''_{ref}(P_y)/C''_{ref,max}}{C''_{P,x,max}/C''_{min}} \times (f_{max} - f_{min}) = K_{f,x} \times C''_{ref}(P_y)$$

$$C''_{min} = \min(C''_{P,1,max}, C''_{P,2,max}, \dots, C''_{P,x,max});$$

$$K_{f,x} = \frac{C''_{min} \times (f_{max} - f_{min})}{C''_{P,x,max} \times C''_{ref,max}} = \text{constant for each DG} \quad (3-15)$$

$$f_x^* = m_x P_x + f_{max} + \Delta f_{x,off} \quad (3-16)$$

In (3-15) and (3-16), subscripts *max* and *min* have again been added to represent the maximum and minimum values of the variable of interest. Additionally, there are a few points to note with reference to (3-15), whose clarifications are summarized as follows.

- i. Parameter C'_{min} is the maximum cost at the maximum power of the least costly existing DG or future DG planned for expansion. In Fig. 3-2 (b), it is hence equal to $C''_{P,3,max}$.
- ii. Parameter $K_{f,x}$ is a constant, whose value differs for different DGs because of the $C''_{P,x,max}$ term in its denominator. For the example in Fig. 3-2 (b), $K_{f,x}$ for the three DGs are related according to $K_{f,1} < K_{f,2} < K_{f,3}$.

- iii. With $K_{f,x}$ given by (3-15), the offset frequency $\Delta f_{x,off}$ computed will not exceed the specified frequency range. For the example in Fig. 3-2 (b), it means $0 \leq \Delta f_{1,off} < \Delta f_{2,off} < \Delta f_{3,off} \leq (f_{max} - f_{min})$.

3.4.1.2 Reactive Power

As explained earlier, the reactive cost curves for the three DGs in Fig. 3-1 is set analogous to active power cost shown in Fig. 3-2 (a) and (b). The same chosen reference function and offset computation in (3-15) can hence be applied to reactive power generation, whose corresponding set of expressions are given in (3-17) and (3-18).

$$\Delta V_{x,off} = \frac{C''_{ref}(Q_y)/C''_{ref,max}}{C''_{P,x,max}/C''_{min}} \times (V_{max} - V_{min}) = K_{V,x} \times C''_{ref}(Q_y)$$

$$K_{V,x} = \frac{C''_{min} \times (V_{max} - V_{min})}{C''_{P,x,max} \times C''_{ref,max}} = \text{constant for each DG} \quad (3-17)$$

$$V_x^* = n_x Q_x + V_{max} + \Delta V_{x,off} \quad (3-18)$$

In addition, with $K_{V,x}$ computed according to (3-17), the following analogical relationships can be derived for the example given in Fig. 3-2 (b).

- i. $K_{v,1} < K_{v,2} < K_{v,3}$.
- ii. $0 \leq \Delta V_{1,off} < \Delta V_{2,off} < \Delta V_{3,off} \leq (V_{max} - V_{min})$.

To illustrate how the proposed droop expressions modify the responses of the microgrid in Fig. 3-1, the active droop expression in (3-16) is applied to the three DGs as an example (the reactive responses are the same, and hence not duplicated here). Noting that $f_1^* = f_2^* = f_3^*$ in the steady state, the relationships obtained from (3-16) are given as follows.

$$(m_1 P_1 - m_2 P_2) + (\Delta f_{1,off} - \Delta f_{2,off}) = 0 \quad (3-19)$$

$$(m_2 P_2 - m_3 P_3) + (\Delta f_{2,off} - \Delta f_{3,off}) = 0 \quad (3-20)$$

The first terms on the left of (3-19) and (3-20) will, no doubt, give rise to proportional power sharing based on ratings if generation costs are not considered. Assuming further that the DGs are equally rated, the resulting power sharing without considering generation costs would then be $P_1 = P_2 = P_3$. Adding the generation costs now will lead to those frequency offsets found in the second terms on the left of (3-19) and (3-20). Values of these second terms will initially be negative since $P_1 = P_2 = P_3$ and $C''_{P,1} > C''_{P,2} > C''_{P,3}$ according to the offset computation given in (6). To nullify these initial negative values, (3-19) and (3-20) infer that the DG generations must automatically adjust to give $P_1 < P_2 < P_3$. Since m_x is negative, the first terms on the left of (3-19) and (3-20) will then be positive, which indeed are needed for cancelling with their accompanied negative second terms in the steady state. The concepts apply to reactive power sharing as well with its results showing that the least costly generator will always produce the largest amount of active and reactive powers, hence giving rise to an overall reduction of TGC for the considered microgrid.

3.4.1.3 Power Limits

With the given relations in Subsection 3.4.1.1(iii) and 3.4.1.2(ii), the proposed cost-based scheme will hence not breach any of the usual frequency and voltage limits. It is however important to clamp the generations of all DGs at their rated values of $P_{x,max}$ and $Q_{x,max}$, regardless of whether they saturate at or higher than f_{min} and V_{min} . The same clamping is needed by the traditional linear droop scheme, and hence does not introduce any additional complexity to the proposed cost-based scheme. The clamping

can, in practice, be done by switching from the droop scheme to a simple proportional-integral (*PI*) scheme. The usual control expressions used with the *PI* controller are given in (3-21) and (3-22), where K_p and K_i are the proportional and integral gains.

$$f_x^* = (P_{x,max} - P_x) \times \left(K_p + K_i/s \right) \text{ when } P_x > P_{x,max} \quad (3-21)$$

$$V_x^* = (Q_{x,max} - Q_x) \times \left(K_p + K_i/s \right) \text{ when } Q_x > Q_{x,max} \quad (3-22)$$

Alternatively, the maximum power limits can also be imposed through current controller reference (i_{dq}^*).

3.4.2 Approximate Reference Cost-Function Based Droop Scheme

As mentioned earlier, the reference quadratic function chosen needs not always be from the most costly DG. To illustrate, an arbitrarily chosen second-order quadratic reference can be used for testing, whose expression is given as follows.

$$C_{ref}''(P_y) = K_{ref} \times P_y'^2 \quad (3-23)$$

Parameter K_{ref} in the expression is included mainly for placing the reference curve $C_{ref}''(P_y)$ maximum value near to the maximum value in most expensive DG cost curve in Fig. 3-2(b) so that a closer number range can be used for better accuracy when implemented and will also ensure frequency and voltage to be within defined range analogous to relation given in above Subsection 3.4.1.1(iii) and 3.4.1.2(ii). Besides the change of reference, the other computation steps given from (3-15) to (3-18) remain unchanged.

Note that the schemes discussed in Section 3.4, including the scheme in this subsection, do not consider cost variations at different power levels. They are therefore insensitive

to any changes in costs, and will not be able to track their variations precisely. For example, if DG 1 is less costly than DG 2 at low load and more costly than DG 2 at high load, the schemes discussed in Section 3.4 will not be able to track this intermediate cost reversal. Despite this drawback, the schemes discussed in Section 3.4 can still be attractive because of their simplicity, which can be a merit for the following cases.

- All DG costs can be approximated by quadratic functions, which is a reasonable assumption in practice.
- The exact DG quadratic cost-functions are not known. Only their maximum full-load and minimum no-load operating costs are known.

For more precise tracking of costs, the scheme proposed in Section 3.5 is recommended, which needless to say, requires all cost-functions to be defined before it can be implemented.

3.4.3 Generation Cost Curves of DGs

The cost function, expressed in (3-1) and rewritten in (3-24), contains two types of coefficients. The first type include coefficients like a_x , b_x , c_x , α_x , β_x , γ_x , ϵ_x for representing the DG behavioral responses. The second type includes $K_{fuel,x}$ and $K_{emm,x}$ for representing the necessary conversion or scaling factors. The fuel and emission behavioral data of internal combustion engines are primarily taken from the existing literature, and then modified or scaled to allow for testing of the proposed schemes. Since real behavioral and cost data is usually not available, and can vary with the chosen technology, capacity, and geographical location (because of different labor and fuel costs), the approach proceeded with in this thesis is to assume that the ICE-based DGs generate in the range of 0.2-0.4\$/kWhr.

The coefficient values used for representing the behavior of the ICE-based generators [120], [121], [123] are then substituted to (3-24), which after minor changes, give the expression in (3-25) for representing DG 1.

$$C_x(P_x) = C_x + K_{o\&m,x}P_x + K_{fuel,x}(a_x + b_xP_x + c_xP_x^2) + K_{emm,x}(\alpha_x + \beta_xP_x + \gamma_xP_x^2 + \epsilon_x \exp(\rho_xP_x)) \quad (3-24)$$

$$C_1(P_1) = C_1 + K_{o\&m,1}P_1 + K_{fuel,1}(20 + 80P_1 + 250P_1^2) + K_{emm,1}(2.5 - 4.047P_1 + 5.638P_1^2 + 1e^{-4} \exp(8.33P_1)) \quad (3-25)$$

The remaining conversion or re-scaling constants $K_{o\&m,1} \sim 0.04$, $K_{fuel,1} \sim 0.002$ and $K_{emm,1} \sim 0.1$, $C_1 \sim 0.4^1$ are then chosen to obtain a total generation cost of 0.52\$/kWhr with capital cost and 0.39\$/kWhr without capital cost for DG 1.

Further simplification eventually leads to the final cost curve given in (3-26) and plotted in Fig. 3-3² for DG 1.

$$C_1(P_1) = 0.4 + 0.04P_1 + 0.02(20 + 80P_1 + 250P_1^2) + 0.1(2.5 - 4.047P_1 + 5.638P_1^2 + 1e^{-4}\exp(8.333P_1)) \quad (3-26)$$

Similarly, for DG 2, its coefficients of $K_{o\&m,2} \sim 0.04$, $K_{fuel,2} \sim 0.002$ and $K_{emm,2} \sim 0.1$, $C_2 \sim 0.76^3$, when substituted to (3-27), gives a total generation cost of 0.62\$/kWhr with capital cost and 0.37\$/kWhr without capital cost for DG 2. Upon simplified, the final cost curve for DG 2 is given by (3-28), which when plotted, gives the diagram in Fig. 3-3².

¹ $C_1 = \frac{\$40,000(cost)}{30kW*20,000hr(life)*0.5(ave\ loading)} = 0.13$ (scaled by 3) = 0.4\$/kWhr

² The costs are scaled by three (3) and $P_{min} \sim 0.05$ is used while plotting the curves in Fig. 3-3.

³ $C_2 = \frac{\$150,000}{30kW*40,000*0.5} = 0.25$ (scaled by 3) = 0.75

$$C_2(P_2) = C_2 + K_{o\&m,2}P_2 + K_{fuel,2}(25 + 100P_2 + 160P_2^2) + K_{emm,2}(4.09 - 5.554P_2 + 6.49P_2^2 + 4e^{-3} \exp(2.857P_2)) \quad (3-27)$$

$$C_2(P_2) = 0.75 + 0.04P_2 + 0.02(2.5 + 10P_2 + 16P_2^2) + 0.1(4.09 - 5.554P_2 + 6.49P_2^2 + 4e^{-3} \exp(2.857P_2)) \quad (3-28)$$

For DG 3, its cost-function in (3-8) (rewritten in (3-29)) composes of the converter efficiency/loss model, maintenance cost, fuel cost, and emission incentive constants. Coefficients related to the converter efficiency/loss are derived from its typical efficiency curve, whose value is mostly 98% or above for loading exceeding 70%. Other scaling factors/constants associated with maintenance, fuel and emission are, on the other hand, chosen to give a total generation cost of 0.066\$/kWhr for DG 3. Upon substituting $K_{o,3} = \eta_3(K_{o\&m,3} + K_{fuel,3} + K_{emm,3}) = 0.98(0.075 + 0.21 - 0.075) = 0.20$ and the typical efficiency curve model to (3-29), the final cost curve is derived as (3-30) for DG 3, whose plot is also drawn in Fig. 3-3².

$$C_x(P_x) = K_{o,x}(P_x + K_{l,x}(v_x + u_x P_x + \omega_x P_x^2)) \quad (3-29)$$

$$C_3(P_3) = 0.2(P_3 + 0.1(0.2 - 0.1P_3 + 0.1P_3^2)) \quad (3-30)$$

Fig. 3-3. Generation cost curves of three DGs $\sim C'_{P,x}(P_x)$

For all cost curves, it should be mentioned that they have been scaled by three with capital costs added to the generation costs of DG 1 and DG 2. This is for demonstrating that scaling and the inclusion of capital costs, which do not depend the actual power generated, have no impact on the desired cost reduction in microgrid.

3.4.4 Experimental Setup

To validate the proposed scheme, the example microgrid with three DGs and loads shown in Fig. 3-1 has been developed in the laboratory, as shown in Fig. 3-4 and Fig. 3-5.

Each of three DG was realized with dc source and complete set of six-switch converter digitally controlled through dSPACE 1103 and dSPACE 1104. The microgrid graphical user interface (GUI) and data management system was also developed for microgrid control and data analysis.

For the schemes described in above section, each converter rating was set at 1 kW with a power factor of 0.8, unless stated otherwise. Parameters and control schematic used for the testing can either be found in Fig. 3-4 or TABLE 3-1.

TABLE 3-1: Experimental frequency, voltage and power ranges

Parameters	Values
$f_{min} \leftrightarrow f_{max}$	49 $\leftrightarrow$ 51Hz
$V_{min} \leftrightarrow V_{max}$	0.95 $\leftrightarrow$ 1.05p.u.
Base Voltage	190V (Line rms)
Base Power	1 kVA
Max. P_x and Q_x	Mentioned in text
Max. P'_x and Q'_x	1.0 each

Fig. 3-4. Experimentally tested microgrid and its DG control schematic

Fig. 3-5. Lab experimental setup

3.4.5 Experimental Results

The proposed scheme is tested with three different microgrid configurations with each subjected to three different load conditions (light, moderate and heavy). The results

obtained are presented as follows with the TGC of the overall microgrid computed by summing up the costs of all DGs, using (3-12).

3.4.5.1 Configuration A – Equally Rated DGs

In configuration A, the three DGs are rated equally at 1 kW with a power factor of 0.8. They have different generation cost curves, as seen from Fig. 3-6(a). Although DG 2 is overall more costly than the rest, a huge part of its cost comes from its no-load cost, as understood from the plot in Fig. 3-6(a). Since no-load cost is always incurred as far as DG is ON regardless of the amount of power generated, it should hence be removed, which then leads to the plot in Fig. 3-6(b) used for the control. Since the most expensive DG is now mostly DG 1, its cost curve is chosen as the reference quadratic function ($C''_{ref}(P_y) = C''_{P,1}(P_1)$). With this choice made, the corresponding parameters computed for droop control are,

$$C''_{min} = \min(0.9124, 0.6798, 0.19) = 0.19$$

$$K_{f,1} = \frac{C''_{min} \times (f_{max} - f_{min})}{C''_{P,1,max} \times C''_{ref,max}} = \frac{0.19(51-49)}{0.9124 \times 0.9124} = 0.456$$

$$K_{f,2} = \frac{C''_{min} \times (f_{max} - f_{min})}{C''_{P,2,max} \times C''_{ref,max}} = \frac{0.19(51-49)}{0.6798 \times 0.9124} = 0.612$$

$$K_{f,3} = \frac{C''_{min} \times (f_{max} - f_{min})}{C''_{P,3,max} \times C''_{ref,max}} = \frac{0.19(51-49)}{0.19 \times 0.9124} = 2.19$$

$$\Rightarrow K_{f,1} < K_{f,2} < K_{f,3}$$

$$K_{v,1} = \frac{C''_{min} \times (V_{max} - V_{min})}{C''_{P,1,max} \times C''_{ref,max}} = \frac{0.19(1.05-0.95)}{0.9124 \times 0.9124} = 0.0228$$

$$K_{v,2} = \frac{C''_{min} \times (V_{max} - V_{min})}{C''_{P,2,max} \times C''_{ref,max}} = \frac{0.19(1.05-0.95)}{0.6798 \times 0.9124} = 0.0306$$

$$K_{v,3} = \frac{C''_{min} \times (V_{max} - V_{min})}{C''_{P,3,max} \times C''_{ref,max}} = \frac{0.19(1.05-0.95)}{0.19 \times 0.9124} = 0.1096$$

$$\Rightarrow K_{v,1} < K_{v,2} < K_{v,3}$$

(a)

(b)

Fig. 3-6. DGs generation cost curves for microgrid configuration “A” (a) $C'_{P,x}(P_x)$ and (b) $C''_{P,x}(P_x)$

Applying them to the proposed droop scheme then leads to a lower TGC than the traditional droop scheme, as seen from Fig. 3-7(a) for the two step increases in load. Power sharing, frequency and voltage variations triggered by the load changes are also shown from Fig. 3-7(b) to Fig. 3-7(e), where it is observed that the least costly DG3 is always producing more, as intended. Moreover, frequency and voltage values produced by the proposed droop scheme are always higher than the traditional droop scheme, whose explanation can be linked to the positive frequency and voltage offsets added according to (3-16) and (3-18). The proposed scheme therefore regulates the microgrid frequency and voltage better, in addition to providing a lower TGC.

(a)

(b)

(c)

(d)

(e)

Fig. 3-7. Microgrid configuration “A” (a) TGC (b) frequency and (c) voltage with the traditional and reference cost-based droop scheme; (d) active and (e) reactive power generated by the DGs with proposed reference cost-based droop scheme

Fig. 3-8. Microgrid configuration “A” (a) active and (b) reactive powers generated by the DGs with the traditional linear droop scheme

For comparison, corresponding active and reactive power waveforms obtained for the three DGs controlled by the traditional droop scheme are also shown in Fig. 3-8. As expected, the three active and reactive power waveforms superimposed on one another since the DGs tested have the same ratings. In the subsequent cases and cost-based schemes, the power sharing results for the traditional droop scheme are not shown since they convey the same information.

To demonstrate its transient responses, per phase voltage waveforms (notated as L1) of the three DGs and current waveform of DG3, controlled by the proposed cost-based droop scheme, are shown in Fig. 3-9 and Fig. 3-10. These figures correspond to a change in load from 32% to 58% (step load change at ~20sec in Fig. 3.7) of the total microgrid capacity, which will in turn cause those slight decreases in voltages and increase in current observed in the two figures. These transitions are smooth and gradual, caused mainly by filtering delays intentionally introduced for computing the average powers.

Fig. 3-9. Microgrid configuration "A" voltage and current waveforms when load is changed from light to moderate (time scale 1sec/div)

Fig. 3-10. Microgrid configuration "A" voltage and current waveforms when load is changed from light to moderate (time scale 500ms/div)

The proposed droop scheme therefore does not introduce any transient complication when compared with the traditional droop scheme.

(a)

(b)

Fig. 3-11. Microgrid configuration “A” (a) TGC with the traditional and approximate cost-based droop scheme (b) active power generated by the DGs with approximate cost-based droop scheme

The experiment was next repeated with the reference quadratic function changed to $C''_{ref}(P_y) = (P_y/P_{y,max})^2$. This modification is to validate the scheme proposed in Section 3.4.2. The results obtained are shown in Fig. 3-11(a) and (b). The former again shows a reduced TGC, while the latter shows that the lower TGC is obtained by making the least costly DG produces more (reactive generation responses are closely similar, and hence not shown here). This is no doubt the intention of the proposed droop scheme.

3.4.5.2 Configuration B – Cost Curves of DG 1 Modified

Configuration B is close to configuration A except with the cost curves of DG 1 changed to those in Fig. 3-12(a) and (b) to further verify the effectiveness of proposed scheme for DG replacement case. The reference quadratic function is however not changed, meaning it is still using the older cost curves of DG 1, which is also not the most costly DG now. This is again for demonstrating that the choice of reference will not critically affect the system like for example causing it to become unstable and droop inherited flexibility for expansion or modification in the network is retained.

(a)

(b)

Fig. 3-12. DGs generation cost curves for microgrid configuration “B” (a) $C'_{P,x}(P'_x)$ and (b) $C''_{P,x}(P'_x)$.

Fig. 3-13. Microgrid configuration “B” (a) TGC with the traditional and reference cost-based droop scheme (b) active power generated by the DGs with approximate reference droop scheme

The results obtained are shown in Fig. 3-13(a) and (b), where a saving in TGC is again achieved by the proposed droop scheme. Unlike configuration A, the results for configuration B in Fig. 3-13(b) show that DG 1 is no longer producing the least power since it is now not the most costly DG, according to the lower plot shown in Fig. 3-11(b).

3.4.5.3 Configuration C – Capacity of DG 2 Doubled

For configuration C, the capacity of DG 2 is doubled to 2kW for demonstrating that the scheme can still function smoothly even with differently rated DGs. The new cost curves used with configuration C are given in Fig. 3-14(a) and (b), where the most costly DG is noted to be DG 2 followed by DG 1 and DG 3.

The experimental results obtained are shown in Fig. 3-15(a) and (b), where a saving in TGC is consistently ensured by the proposed scheme.

(a)

(b)

Fig. 3-14. DGs generation cost curves for microgrid configuration “C” (a) $C'_{P,x}(P_x)$ and (b) $C''_{P,x}(P_x)$

(a)

(b)

Fig. 3-15. Microgrid configuration “C” (a) TGC with the traditional and reference cost-based droop scheme (b) active power generated by the DGs with approximate reference droop scheme

TABLE 3-2: Summary of TGC savings achieved by the proposed droop scheme

Loading [^]	Configuration A				Configuration B		Configuration C	
	Reference		Approx.		Reference		Reference	
	Saving *	Saving **	Saving *	Saving **	Saving *	Saving **	Saving *	Saving **
Light	0%	0%	0%	0%	0%	0%	1.6%	13.8%
Moderate	9%	42%	9%	42%	7%	36.8%	16%	42.4%
Heavy	8.8%	23%	8.8%	23%	6.7%	19.5%	12%	20.9%

[^] In terms of total DGs/Microgrid generation capacity

* TGC saving with no-load cost of DG included

** TGC saving with no-load cost of DG not included

Comparing with the earlier two configurations, the savings obtained here is also larger mainly because of the more widely spaced cost curves shown in Fig. 3-14(b). This makes the DGs more different with more savings to harvest.

3.4.5.4 Discussion

The savings in costs achieved by the proposed droop scheme are summarized in TABLE 3-2 for the three tested configurations. These savings are computed from the overall microgrid TGC, which as mentioned earlier, is obtained by summing the costs of all DGs including their no-load costs. The savings can certainly be re-computed with the no-load costs removed.

Clearly, the percentage savings will be larger when the no-load costs are removed. These are after all fixed costs that will not change with the actual powers generated.

3.5 Cost-Based Droop Scheme with Accurate Cost Curves Tracing

The droop scheme described in the following sections is also developed based on reducing the overall generation cost of the considered microgrid. Its operating principles are however different from those cost-based schemes described earlier. The earlier schemes can certainly reduce generation cost of the considered microgrid, but with restrictions since they are developed with the DG cost curves considered partially. They are therefore not able to track the cost curve variations accurately. An alternative scheme that tracks the cost curve variations more sharply is therefore proposed here to arrive at lower generation costs at all operating points. Apart from the similar normalization process for cost-function curves, the methodology for the proposed scheme is entirely different than the aforementioned droop schemes.

Apart from the accurate tracing of cost, the reactive power sharing among DGs is achieved based on the reactive power generation cost-functions unlike previous schemes where the reactive power sharing was set analogous to active power sharing.

3.5.1 Generation Cost Curves of DGs

The active power cost-functions defined in Section 3.3.1 and Section 3.3.2 are used to illustrate the proposed droop scheme in the following sections. The active and reactive power cost curves used in the proposed cost-based droop scheme are given in the following paragraphs.

3.5.1.1 Active Power Cost

The proposed cost-based droop scheme is explained with the example microgrid shown in Fig. 3.16. Constant coefficients used for representing behaviors of the internal combustion engines found in that microgrid are taken from the existing literature [120], [121], [123], and then re-scaled to give a generation cost of between 0.2 and 0.4\$/kWhr for the ICE-based DGs.

The re-scaled constants $a_x, b_x, c_x, \alpha_x, \beta_x, \gamma, \epsilon_x, \rho_x$ for the ICE-based DGs [120] are substituted in (3-1), rewritten by (3-31), to arrive at (3-32) for DG 1 and (3-33) for DG2. The rescaling factors $K_{o\&m,1} = K_{o\&m,2} \sim 0.04$, $K_{fuel,1} = K_{fuel,2} \sim 0.001$ and $K_{emm,1} = K_{emm,2} \sim 0.02$ are then chosen to give per-unit generation costs of 0.32\$/kWhr for DG1 and 0.30\$/kWhr for DG2. Upon substituting these values to (3-32) and (3-33), the final expressions for the cost curves are derived as (3-34) for DG1 and (3-35) for DG 2.

$$C_x(P_x) = K_{o\&m,x}P_x + K_{fuel,x}(a_x + b_xP_x + c_xP_x^2) + K_{emm,x}(\alpha_x + \beta_xP_x + \gamma_xP_x^2 + \epsilon_x \exp(\rho_xP_x)) \quad (3-31)$$

$$C_1(P_1) = K_{o\&m,1}P_1 + K_{fuel,1}(10 + 60P_1 + 140P_1^2) + K_{emm,1}(2.5 - 6.047P_1 + 5.638P_1^2 + 25e^{-3} \exp((3.33P_1))) \quad (3-32)$$

$$C_2(P_2) = K_{o\&m,2}P_2 + K_{fuel,1}(40 + 120P_2 + 20P_2^2) + 0.02(4.09 - 5.554P_2 + 6.49P_2^2 + 10e^{-3} \exp(2.857P_2)) \quad (3-33)$$

$$C_1(P_1) = 0.04P_1 + 0.01(1 + 6P_1 + 14P_1^2) + 0.02(2.5 - 6.047P_1 + 5.638P_1^2 + 25e^{-3} \exp(3.33P_1)) \quad (3-34)$$

$$C_2(P_2) = 0.04P_2 + 0.01(4 + 12P_2 + 2P_2^2) + 0.02(4.09 - 5.554P_2 + 6.49P_2^2 + 10e^{-3} \exp(2.857P_2)) \quad (3-35)$$

For DG 3, its constant coefficients for representing converter efficiency/loss are obtained from typical efficiency curve, showing 98% efficiency beyond 70% loading. Other scaling factors or constants for converting maintenance, fuel and emission incentives to costs are chosen to give a per-unit generation cost of 0.051\$/kWhr for DG3. Substituting the the typical efficiency curve model and $K_{o,3} = \eta_3(K_{o\&m,3} + K_{fuel,3} + K_{emm,3}) = 0.98(0.025 + 0.051 - 0.025) = 0.05$ in (3-8) (rewritten as (3-36)), the final cost curve for representing DG3 is eventually derived as (3-37).

$$C_x(P_x) = K_{o,x}(P_x + K_{l,x}(v_x + u_x P_x + \omega_x P_x^2)) \quad (3-36)$$

$$C_3(P_3) = 0.05(P_3 + 0.1(0.2 - 0.1P_3 + 0.1P_3^2)) \quad (3-37)$$

DG 1 and DG 2 active power cost curves are then plotted using equations (3-34) and (3-35), whereas DG 3 cost curve is plotted using equation (3-37), and subsequently cost-curves are normalized based on power using equation (3-9), as shown in Fig. 3-17(a)⁴. These cost-curves are further normalized by subtracting the no-load cost using equation (3-10), and plotted in Fig. 3-17 (b).

From the plotted active power cost curves, the relationship observed from Fig. 3-17(a) can obviously be written as follow for all active power values indicated.

$$C'_{P,2} > C'_{P,1} > C'_{P,3}$$

After removal of no-load fix cost, it shall however be noted that generation cost now varies as loading increases and it can be written as,

$$C'_{P,1} > C'_{P,2} > C'_{P,3} .$$

⁴ $P_{min} \sim 0.05$ is used while plotting the cost-curves of DGs in Fig. 3-17.

Fig. 3-16. Microgrid configuration I with three DGs

Fig. 3-17. Active power generation cost curves of three DGs (a) $C'_{P,x}(P_x)$ and (b) $C''_{P,x}(P_x)$.

3.5.1.2 Reactive Power Cost-Function

As mentioned earlier, unlike active power, reactive power generation ideally consumes no fuel or energy, and should hence have zero cost. In practical, extra copper losses in stator and rotor winding of the synchronous generator and switching & conduction losses in the inverter interfaced DGs are attributed due to reactive power generation [141]. The synchronous generator losses can be decomposed into I^2R and eddy current

losses, whereas, the converter losses can be decomposed into voltage dependant and current dependant losses. Theoretically the losses in synchronous generator as well as converter interface DGs can be represented by a second order quadratic equation and main difference would be constant parameters values used for the considered DGs.

There is no-load cost associated with each DG. For costing purpose, if DG is designed to supply both active power and reactive power then the no-load cost can be attributed to either active power cost or reactive power cost.

In literature, various approaches have, so far, been suggested to demonstrate the cost relationship between reactive power generation and its accompanied active power losses [140]-[145]. The most straightforward would, of course, be direct measurement, and then perform a curve fit with the collected active and reactive power data. The collection process might however be lengthy, even if feasible.

Alternatively, the reactive power cost of each DG can be estimated by defining its accompanied active power loss $P_{Q,loss}$ as a percentage ϑ of the reactive power Q_x generated. This estimation can be seen in [142] and [141], where the power losses of a synchronous generator and a inverter can be approximated to be 3% and 5% of their respective reactive powers generated. Their related cost-functions $C_{Q,x}(Q_x)$ can hence be written as (3-38), which like the earlier active power cost-functions, should be quadratic because of their dependence on an active power term. However, it shall be noted that losses due to the reactive power generation depend on the active power being generated by a DG. This dependence shows that the losses due to the reactive power are more when DG/converter is generating less active power and vice versa [140]. For an accurate reactive power costing, this dependence should also be considered.

For illustration, the reactive cost curves $C'_{S,x}(P_x + P_{x,Q_{loss}})$ and $C''_{Q,x}(Q_x)$ assumed for the three DGs shows in Fig. 3.16 are plotted in Fig. 3-18(a) and (b), respectively. These

Fig. 3-18. Generation cost curves of three DGs (a) $C'_{S,x}(P_x + P_{x,Q_{loss}})$ and (b) $C''_{Q,x}(Q_x)$.

curves are plotted with the normalized reactive power $Q'_x = Q_x/Q_{x,max}$ along the x -axis. As mentioned earlier, the no-load cost is already attributed to active power generation costing therefore $C'_{Q,x}(Q_x = 0) \approx 0$ in (3-38).

$$C_{Q,x}(Q_x) = C_{Q,x}(P_{Q,loss} = \vartheta Q_x) = C_{S,x}(P_x + P_{x,Q_{loss}}) - C_{P,x}(P_x)$$

$$C'_{Q,x}(Q_x) = C_{Q,x}(Q_x)/Q_{x,max}$$

$$C''_{Q,x}(Q_x) = C'_{Q,x}(Q_x) - C'_{Q,x}(Q_x = 0) \approx C'_{Q,x}(Q_x) \quad (3-38)$$

From the plotted reactive power cost curves, the relationship observed from Fig. 3-18(b) can be written as $C'_{Q,1} > C'_{Q,2} > C'_{Q,3}$ for all reactive power loading values indicated.

3.5.1.3 Total Generation Cost of Overall Mircogrid

With the active and reactive power cost terms defined for the individual DGs, the TAGC and TRGC values of the overall microgrid can be written as (3-39), where subscripts “ W ” and “ WO ” have been added to distinguish values with and without no-

load costs included $C'_{P,x}(P_x = 0)$ in (3-10) and $C'_{Q,x}(Q_x = 0)$ in (3-38). Where necessary, the TAGC and TRGC values can further be summed to give the total generation cost (TGC) of the microgrid, whose expressions are also given in (3-39).

$$\begin{aligned} TAGC_W &= \sum C_{P,x}(P_x) = \sum \{C'_{P,x}(P_x) * P_{x,max}\}; \quad TAGC_{WO} = \sum \{C''_{P,x}(P_x) * P_{x,max}\} \\ TRGC_W &= \sum C_{Q,x}(Q_x) = \sum \{C'_{Q,x}(Q_x) * Q_{x,max}\}; \quad TRGC_{WO} = \sum \{C''_{Q,x}(Q_x) * Q_{x,max}\} \\ TGC_W &= TAGC_W + TRGC_W; \quad TGC_{WO} = TAGC_{WO} + TRGC_{WO} \end{aligned} \quad (3-39)$$

The cost-function curves discussed in above sections are used to illustrate the cost-based droop scheme with accurate curve tracing.

3.5.2 Methodology

The basic droop equations reviewed in Chapter 2 are expressed with slight modification in (3-40) and (3-41), where x , f , V , $\{P$ and $Q\}$, and $\{max$ and $min\}$ are the DG unit number, frequency, terminal voltage, active and reactive power generations, and their corresponding maximum and minimum values, respectively.

$$f_x^* = f_{max} - m_x P_x; \quad m_x = \frac{f_{max} - f_{min}}{P_{x,max}} \quad (3-40)$$

$$V_x^* = V_{max} - n_x Q_x; \quad n_x = \frac{V_{max} - V_{min}}{Q_{x,max}} \quad (3-41)$$

Instead of directly depending on the power values shown in (3-40) and (3-41), the proposed cost-based droop scheme adjusts its frequency and voltage commands in accordance to the active and reactive power cost-functions. The resulting droop expressions are shown in (3-42) and (3-43).

$$f_x^* = f_{max} - m_x * C''_{P,x}(P_x); \quad m_x = \frac{f_{max} - f_{min}}{C''_{P,max}} \quad (3-42)$$

$$V_x^* = V_{max} - n_x * C''_{Q,x}(Q_x); \quad n_x = \frac{V_{max} - V_{min}}{C''_{Q,max}} \quad (3-43)$$

In (3-42) and (3-43), two new terms are included and notated as $C''_{P,max}$ and $C''_{Q,max}$. These terms are for extracting the highest generation costs among the DGs at full-load (FL) when $P_x = P_{x,max}$ and $Q_x = Q_{x,max}$. For the example microgrid in Fig. 3.16, whose cost curves are given in Fig. 3-17(b) and Fig. 3-18(b), $C''_{P,max}$ and $C''_{Q,max}$ are respectively expressed as (3-44) and (3-45).

$$C''_{P,max} = \max\{C''_{P,1}(P_{1,max}), C''_{P,2}(P_{2,max}), C''_{P,3}(P_{3,max})\} = C''_{P,1}(P_{1,max}) \quad (3-44)$$

$$C''_{Q,max} = \max\{C''_{Q,1}(Q_{1,max}), C''_{Q,2}(Q_{2,max}), C''_{Q,3}(Q_{3,max})\} = C''_{Q,1}(Q_{1,max}) \quad (3-45)$$

Substituting (3-44) and (3-45) into (3-42) and (3-43) then leads to those active and reactive droop curves shown in Fig. 3-19(a) and (b). Although the droop curves are no longer linear, the same droop principles are still applicable, which means in the steady state, a single fixed frequency and voltage can be substituted into (3-42) and (3-43). For

Fig. 3-19. DGs droop curves for the cost-based droop scheme (a) active power vs. frequency and (b) reactive power vs. voltage

the example microgrid illustrated in Fig. 3-16, Fig. 3-17 and Fig. 3-18, it means substituting $f_1^* = f_2^* = f_3^* = f$ and $V_1^* = V_2^* = V_3^* = V$ to get (3-46) and (3-47).

$$C_{P,1}''(P_1) = C_{P,2}''(P_2) = C_{P,3}''(P_3) \quad (3-46)$$

$$C_{Q,1}''(Q_1) = C_{Q,2}''(Q_2) = C_{Q,3}''(Q_3) \quad (3-47)$$

The equalities in (3-46) and (3-47) are equivalent to drawing a horizontal line in Fig. 3-17(b) and another in Fig. 3-18(b). The active and reactive powers produced by the DGs can then be read from their respective intersecting points. The common trend noted from the read values will surely be the case of the least costly DG producing more, and vice versa. This is no doubt the intention of the proposed cost-based droop scheme. Alternatively, the horizontal lines can be drawn in Fig. 3-19(a) and (b) for reading out the power values, which are again appropriate since $f_1^* = f_2^* = f_3^* = f$ and $V_1^* = V_2^* = V_3^* = V$. In practice, the reactive powers read from Fig. 3-19(b) might deviate slightly due to differences in line impedances and other system parameters. The deviation can be minimized by applying the same compensation techniques proposed earlier for the traditional linear droop scheme reviewed in Chapter 2, and will hence not be repeated here. The overall microgrid TAGC and TRGC can then be found by summing the individual DG active and reactive costs, as summarized in (3-39), whose values will surely be lower than those of the traditional droop scheme. This expectation is independent of the quadratic cost-functions used. Other cost patterns will also give the same results so long as they represent the generation costs of the DGs.

It must however be emphasized that the droop coefficients m_x and n_x computed in (3-42) and (3-43) should be divided by $C_{P,max}''$ and $C_{Q,max}''$, and not the individual DG maximum costs $C_{P,x}''(P_{x,max})$ and $C_{Q,x}''(Q_{x,max})$ at full load. Else, the equalities in (3-46) and (3-47) will become (3-48) and (3-49) which depend also on the individual DG full-

load costs. This dependence is not encouraged since it causes the DG with the lowest individual full-load costs to produce less powers, and hence smaller $C''_{P,x}(P_x)$ and $C''_{Q,x}(Q_x)$ to counter the smaller $C''_{P,x}(P_{x,max})$ and $C''_{Q,x}(Q_{x,max})$.

$$\frac{C''_{P,1}(P_1)}{C''_{P,1}(P_{1,max})} = \frac{C''_{P,2}(P_2)}{C''_{P,2}(P_{2,max})} = \frac{C''_{P,3}(P_3)}{C''_{P,3}(P_{3,max})} \quad (3-48)$$

$$\frac{C''_{Q,1}(Q_1)}{C''_{Q,1}(Q_{1,max})} = \frac{C''_{Q,2}(Q_2)}{C''_{Q,2}(Q_{2,max})} = \frac{C''_{Q,3}(Q_3)}{C''_{Q,3}(Q_{3,max})} \quad (3-49)$$

3.5.3 Operating Limits

The proposed cost-based droop scheme with accurate cost curves tracking operates fine in theory, as explained above. To further demonstrate that it does not violate the usual limits set for droop operation, a short discussion is documented below, before describing modifications in Subsection 3.5.4 that can extend the scheme to include other factors for consideration.

As seen from Fig. 3-19(a) and (b), the upper frequency and voltage limits, notated as $f_{max} = 51\text{Hz}$ and $V_{max} = 1.05p.u.$, are reached but not exceeded when the DGs produce no power. The lower limits of $f_{min} = 49\text{Hz}$ and $V_{min} = 0.95p.u.$ are however reached only by the most expensive DG when it produces $P_{1,max}$ and $Q_{1,max}$. The other two DGs will have their generations clamped at $P_{x,max}$ and $Q_{x,max}$ ($x = 2$ and 3), before their frequency and voltage commands lower to f_{min} and V_{min} . The proposed cost-based scheme will hence not breach any of the usual frequency and voltage limits, even though it uses unconventional nonlinear droop curves. It is however important to clamp the generations of all DGs at their rated values of $P_{x,max}$ and $Q_{x,max}$, regardless of whether they saturate at or higher than f_{min} and V_{min} . The same clamping method

discussed in above Subsection 3.4.1.3 can be used to clamp the power within maximum. These limit equation are rewritten here (3-50) and (3-51).

$$f_x^* = (P_{x,max} - P_x) \times \left(K_p + K_i/s \right) \text{ when } P_x > P_{x,max} \quad (3-50)$$

$$V_x^* = (Q_{x,max} - Q_x) \times \left(K_p + K_i/s \right) \text{ when } Q_x > Q_{x,max} \quad (3-51)$$

3.5.4 Cost-Based Droop Scheme with DGs Rating Considered

Where desired, the cost-based scheme presented can be modified to include other factors for consideration. To illustrate, this subsection shows how the traditional objective of proportional power sharing based on DG ratings can be incorporated to the cost-based droop scheme. The modified droop expressions used are given in (3-52) and (3-53), which in common, involve the multiplication of the normalized powers P'_x and Q'_x to the original two expressions listed in (3-42) and (3-43). Although (3-52 and (3-53) are feasible expressions, their usage is generally not encouraged since they lead to higher microgrid costs than the cost-based scheme, even though they are still lower than those of the traditional droop scheme. Their inclusion here is therefore merely to illustrate how other factors of consideration can be added only when necessary.

$$f_x^* = f_{max} - m_x C_{P,x}''(P_x) \times P'_x \quad (3-52)$$

$$V_x^* = V_{max} - n_x C_{Q,x}''(Q_x) \times Q'_x \quad (3-53)$$

3.5.5 Experimental Setup

The performance verification of the proposed cost-based droop scheme was done through the lab experiment for the three different microgrid configurations. The experimental setup detail has already been given in above Section 3.4.4. For configuration A, the three DGs tied to the microgrid were realized with the same

converters, whose topology, parameters and control blocks for the proposed scheme are shown in either Fig. 3.20 or TABLE 3-3.

Fig. 3-20. Experimental setup and control schematic for DG1

TABLE 3-3: Droop parameters used for testing

Parameters	Values
$f_{min} \leftrightarrow f_{max}$	49 $\leftrightarrow$ 51Hz
$V_{min} \leftrightarrow V_{max}$	0.95 $\leftrightarrow$ 1.05p.u.
Base Voltage	190V (Line rms)
Base Power	1 kVA
Max. P_x	1kW for all unless stated otherwise
Max. Q_x	0.75kVAr for all
Max. P'_x and Q'_x	1.0 each
$C''_{P,1}(P_{1,max})$	0.246
$C''_{P,2}(P_{2,max})$	0.199
$C''_{P,3}(P_{3,max})$	0.047
$C''_{Q,1}(Q_{1,max})$	0.01212
$C''_{Q,2}(Q_{2,max})$	0.00815
$C''_{Q,3}(Q_{3,max})$	0.001894
m_x	8.13
n_x	8.25

3.5.6 Experimental Results

The experiment was carried out to test three different microgrid configurations with each subjected to load changes from 25%, 50% and then to 75% of the total microgrid capacity. Results obtained for the three cases are discussed as follows.

3.5.6.1 Configuration I

In configuration I, all DGs in the microgrid have the same 1kW maximum power, but with different cost shown in Fig. 3-17 and Fig. 3-18. Their respective droop curves based on proposed scheme are shown in Fig. 3-19 and Fig. 3-21. With these operating curves, the load changes cause the microgrid frequency and voltage to droop to according the operating points marked in Fig. 3-21(a) and Fig. 3-21(b) for the traditional scheme, and Fig. 3-21(c) and Fig. 3-21(d) for the cost-based scheme. Experimental results linked to these operating points can be found in Fig. 3-22, Fig. 3-23 and Fig. 3-24 for the three tested load conditions. For the traditional droop scheme, as anticipated and confirmed by Fig. 3-22(a) and (b), active and reactive powers are always shared equally among the DGs because of their similar power ratings. The expectations noted from Fig. 3-21(c) are a higher active power produced by DG 3 and a lower active power produced by DG 2. These expectations are confirmed by the results shown in Fig. 3-22(c), and are in agreement with Fig. 3-17(b), where the least costly DG is always DG 3 and the most costly is DG 2 for individual active power generation by DG 2 below 60% ($P_2' < 0.6$). The number of 60% should however not be confused with the percentage loading, which as mentioned earlier, is given in terms of the total microgrid capacity, and not the individual DG capacity. It shall be noted that cost-curves of all DGs are being traced accurately and power produced follow cost curves variation, for example, as shown in Fig. 3-22(c), DG 1 being less costlier than

(a)

(b)

(c)

(d)

Fig. 3-21. Microgrid configuration “I” (a), (b) active and reactive power droop lines used by the traditional scheme, and (c), (d) active and reactive power droop curves used by the proposed scheme, showing operating points under three different load conditions

(a)

(b)

(c)

(d)

Fig. 3-22. Microgrid configuration “I” (a), (b) active and reactive power sharing of the traditional scheme, (c), (d) active and reactive power sharing of the cost-based scheme under three different load conditions

DG 2 up to its 60% ($P_1' < 0.6$) loading produce more power than DG 2 during loading interval one and two. However, during third loading interval, DG 1 and DG 2 produce equal power at 60% ($P_1' = 0.6$) loading since the generation cost of DG 1 and DG 2 are same at 60% loading, as shown in Fig. 3-17(b). The same reasoning can be applied to reactive power sharing, where Fig. 3-18(b), Fig. 3-21(d) and Fig. 3-22(d) demonstrate that the least costly DG 3 produces the most reactive power, while the most costly DG 1 produces the least reactive power.

With generation costs considered, the proposed scheme also leads to improved frequency and voltage regulations (lower frequency and voltage drops as load increases). This can be seen from Fig. 3-23(a) and (b), which show the experimentally

(a)

(b)

Fig. 3-23. Microgrid configuration “I” (a) frequency and (b) voltage regulations of both schemes under three different load conditions

captured frequency and voltage variations corresponding to those operating points marked in Fig. 3-21(a) to Fig. 3-21(d). The improved performances of the cost-based scheme are expected since it forces the least costly DG 3 to dominate the power generation process. The least costly DG3, in turn, regulates frequency and voltage better due to its more narrowly confined active and reactive power droop characteristics shown in Fig. 3-21(c) and (d).

Summing up the three DG costs then gives the $TAGC_W$ and $TRGC_W$ of the overall microgrid according to (3-39), whose variations are shown in Fig. 3-24(a) and (b), together with those obtained from the traditional linear droop scheme. Clearly, the cost-based droop scheme leads to lower costs for the microgrid. The savings with and

(a)

(b)

Fig. 3-24. Microgrid configuration “T” (a) active power cost $TAGC_W$ comparison and (b) reactive power cost $TRGC_W$ comparison of microgrid under three different load conditions

without no-load costs included (see(3-39)) are also summarized in TABLE 3-4 for the three load conditions tested. The percentages saved are larger during the second interval, as compared to the first. The reason is because differences among the cost curves in Fig. 3-17 (b) and Fig. 3-18(b) are more prominent at higher generated powers. However, as the generated powers increase further, the savings in the third interval increase less steeply since the cheapest DG 3 has already saturated at its maximum power values. The saturation causes DG 3 to contribute no further savings, hence resulting in smaller increases in the third interval.

TABLE 3-4: Percentage TAGC and TRGC savings of the cost-based droop scheme as compared to the traditional linear droop scheme (“W” and “WO” stand for with and with no-load(NL) costs $C_{P,x}$ ($P_x=0$) AND $C_{Q,x}$ ($Q_x \approx 0$)

Loading (% of Total Microgrid Capacity)	Configuration I		Configuration II	Configuration III
	% <i>TAGC</i> <i>Saving</i>	% <i>TRGC</i> <i>Saving</i>	% <i>TAGC Saving</i>	% <i>TAGC Saving</i>
25%	1.7% (W)	8.0%	4.5% (W)	1.2% (W)
	43.7% (WO)		23% (WO)	5.8% (WO)
50%	10.9% (W)	27.0%	17% (W)	9.1% (W)
	32.6% (WO)		36% (WO)	19.4% (WO)
75%	13.3% (W)	24.2%	12.1% (W)	14% (W)
	24.6% (WO)		18.5% (WO)	21.7% (WO)

3.5.6.2 Configuration II

Configuration II is the same as configuration I, but with the rating of DG 2 doubled to 2kW, as shown in Fig. 3-25. The active power cost curves of the DGs are also rearranged, as shown in Fig. 3-26(a) and (b). Applying the same cost-based droop scheme then leads to the re-organized active power sharing shown in Fig. 3-27(a), where the most costly DG 2 produces the least amount of normalized active power P_2' , while the least costly DG 3 produces the most. However, since the rating of DG 2 is doubled, its actual active power generated P_2 is also doubled, causing it to be higher than $P_1 = P_1'$ and $P_3 = P_3'$ in Fig. 3-27(a) (ratings of DG 1 and DG 3 are 1kW each). Their sum representing TAGC_w of the overall microgrid is then traced in Fig. 3-27 (b), together with that obtained from the traditional linear droop scheme.

The savings noted from the figure and fourth column of TABLE 3-4 again demonstrate the effectiveness of the proposed cost-based droop scheme, even if the DGs are rated differently.

Fig. 3-25. Microgrid configuration “II” with DG 2 capacity doubled

(a)

(b)

Fig. 3-26. Microgrid configuration “II” active power cost curves (a) $C'_{P,x}(P'_x)$ and (b) $C''_{P,x}(P'_x)$.

(a)

(b)

Fig. 3-27. Microgrid configuration “II” (a) active power sharing and (b) active power cost $TAGC_W$ comparison of microgrid under three different load conditions

3.5.6.3 Configuration III

In Configuration III, an extra 1kW DG 4 added as shown in Fig. 3-28 to test the performance of the cost-based scheme with four DGs operated in parallel. The cost curves of the DGs are re-organized accordingly, as shown in Fig. 3-29(a) and (b). The cost differences are however not considered by the traditional scheme, which will hence leads to equal power sharing among the DGs, as already demonstrated for Configuration I. With the cost characteristics considered, results from the cost-based scheme are prominently different as shown in Fig. 3-30(c) where the cheapest DG3 is again made to produce the most active power. That, in turn, leads to sizable savings in costs reflected by those waveforms shown in Fig. 3-30(d) and summarized in the last column of TABLE 3-4.

Fig. 3-28. Microgrid configuration “III” with four DGs

(a)

(b)

Fig. 3-29. Microgrid configuration “III” (a) active power cost curves $C'_{P,x}(P_x)$ and (b) $C''_{P,x}(P_x)$

(a)

(b)

Fig. 3-30. Microgrid configuration “III” (a) active power sharing and (b) active power cost $TAGC_w$ comparison of microgrid under three different load conditions

3.6 Stability and Extended Applications of Cost-Based Droop Schemes

Schemes

3.6.1 Stability of Cost-Based Droop Schemes

In this section, stability of the cost-based droop schemes is discussed based on formulated small-signal mathematical expressions. The same small-signal analysis has earlier been applied to the traditional droop scheme, whose differences from the cost-based schemes are solely concentrated in their droop expressions. The rest of the system remains unchanged for the two types of droop schemes. Earlier discussed results for the traditional droop scheme can therefore be borrowed for studying stability of the proposed cost-based schemes.

As reviewed in Section 2.2.4.2, earlier research has concluded that droop gains or

Fig. 3-31. Block diagram showing droop controlled converter

coefficients have to be chosen appropriately to avoid stability concerns. To do that now for the proposed cost-based schemes, a non-minimal state-space model has to be developed for the system, linking its input and output with an averaged converter, output filter and controller models. The derived state-space models for the traditional and cost-based droop systems (shown in Fig. 3-31) are provided in **Appendix-A**, from which finite matrices for representing both schemes are extracted and listed below.

Finite matrix for representing system controlled by the traditional droop scheme is given in (3-54).

$$A_{DG} = \begin{bmatrix} 0 & -m & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & \frac{-n k_{vp} k_{ip}}{L_f} & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1 - k_{vp} k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & 0 & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1 - k_{vp} k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \quad (3-54)$$

Finite matrix for representing system controlled by the cost-based droop schemes discussed in Section 3.4 is provided in (3-55).

$$A_{DG} = \begin{bmatrix} 0 & -m + \frac{K_f K_b}{P_{rated}} + 2K_f K_c & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & 0 & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1 - k_{vp} k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & \frac{(-n + \frac{K_f K_b}{Q_{rated}} + 2K_f K_c) k_{vp} k_{ip}}{L_f} & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1 - k_{vp} k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \quad (3-55)$$

Finite matrix for representing system controlled by the cost-based droop schemes discussed in Section 3.5 is provided in (3-56).

$$A_{DG} = \begin{bmatrix} 0 & -m_c(\frac{Kb}{P_{rated}} + 2Kc) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & 0 & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1-k_{vp}k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & \frac{-n_c(\frac{Kb}{Q_{rated}} + 2Kc)k_{vp}k_{ip}}{L_f} & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1-k_{vp}k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \quad (3-56)$$

The above matrices show that the stability contributing droop gains of the cost-based schemes are always lower than those of the traditional droop scheme if the same voltage and frequency ranges are considered for both schemes. Justifications for this observation can be found in (3-57) and (3-58), deduced from (3-54), (3-55) and (3-56). The left halves of (3-57) and (3-58) show the stability contributing factors of the cost-based scheme, while their right halves show the stability contributing droop gains of the traditional scheme. The former are obviously always smaller because of the additional frequency offsets introduced by the cost-based schemes described in Section 3.4. More precisely, these offsets cause the droop gains of the less costly DGs to decrease. The same reason can be applied to the droop schemes presented in Section 3.5, where the droop gains of the less costly DGs have been reduced. This can be seen from the droop curves of the proposed cost-based scheme shown in Fig. 3.18.

Comparison of stability contributing droop gains of the cost-based droop scheme described in Section 3.4 with the traditional droop scheme:

$$\left| -m + \frac{K_f K b}{P_{rated}} + 2K_f K c \right| < |-m|$$

$$\left| -n + \frac{K_f K b}{Q_{rated}} + 2K_f K c \right| < |-n| \quad (3-57)$$

Comparison of stability contributing droop gains of the cost-based droop scheme described in Section 3.5 with the traditional droop scheme:

$$\left| -m_c \left(\frac{K b}{P_{rated}} + 2K c \right) \right| < |-m|$$

Since,

$$\left| -\frac{f_{max} - f_{min}}{C_{P,max}''} \left(\frac{K b}{P_{max}} + 2K c \right) \right| < \left| -\frac{f_{max} - f_{min}}{P_{max}} \right|$$

$$\left| -\frac{\left(\frac{K b}{P_{max}} + 2K c \right)}{C_{P,max}''} \right| < \left| -\frac{1}{P_{max}} \right| \quad (3-58)$$

It is therefore important to choose the droop gains or coefficients properly, which upon ensured, will always keep the operating frequency and voltage ranges of the DGs within defined limits ($\Delta V_{mg} = V_{max} - V_{min}$; $\Delta f_{mg} = f_{max} - f_{min}$). This behavior is no different from that exhibited by the traditional droop scheme, and has earlier been demonstrated by the obtained experimental results, which are both stable and operate within the defined voltage and frequency limits under all tested load conditions.

Note that the above mentioned stability comparison method might not be comprehensive, especially for the DGs with highly non-linear cost-curves, where the droop gains with the proposed cost-based scheme will be varying. Under such condition, the more appropriate way would be to determine the stability of the proposed schemes at more than one equilibrium points.

3.6.2 Cost-Based Droop Schemes for LV Resistive Network

Although formulated with an inductive network in mind, the proposed cost-based droop schemes can be used with a resistive microgrid after applying a suitable decoupling scheme. Among the decoupling schemes found in the literature, one popular method is to add predominantly inductive virtual impedances at the outputs of the DGs. The resulting controlled network then appears inductive, allowing both traditional and proposed cost-based droop schemes to be applied without significant changes (see Fig. 3-32 for an example illustration). Because of that, application of the cost-based schemes to a resistive network will not be elaborated further.

Fig. 3-32. Cost-based droop controller with virtual impedance loop

3.6.3 Secondary Control for Cost-Based Droop Schemes

Like most, if not all, droop schemes, the proposed cost-based droop schemes require slight voltage and frequency deviations, which can be restored back to their nominal values by an added secondary control layer. The demanded secondary control is no different from that tested for the traditional droop schemes. It involves a central controller and some communication links with low bandwidth for relaying voltage and frequency offsets to the locally controlled DGs, like demonstrated in Fig. 3-33. Since the response time of this secondary controller is usually tuned to be much slower, it will not interfere with the local droop controllers. The secondary and local controllers can

therefore be designed separately. The former is however not elaborated in the thesis since it is no different from that implemented for the traditional droop scheme.

Fig. 3-33. Microgrid architecture showing cost-based droop scheme with secondary control for frequency and voltage restoration to nominal value

3.7 Conclusions

In total, two different droop schemes (each with two variants) with generation costs of the DGs considered have been discussed in this chapter. Unlike existing droop schemes which consider only DG ratings, the proposed droop schemes achieve a reduction of TGC for the considered microgrid by making the less costly DGs produce more power. This expectation has been proven in experiments for various microgrid configurations when subjected to different load conditions. While enforcing the cost reduction, power, voltage and frequency limits of the DGs and microgrid are never exceeded, even when modifications are made to the network configuration like, for example, adding of a new DG. The proposed cost-based droop schemes are therefore demonstrated to have merits, which are presently not yet discussed in the open literature.

A common feature demonstrated by the cost-based droop schemes proposed here is the omission of the DG no-load fixed costs. This omission is fine if the DGs have expensive start-stop requirements, and are hence always in operation. For cases where some DGs can be temporarily turned off, their no-load costs and accompanied variations should not be omitted when making power dispatch decisions for the DGs. Omitting the no-load costs in those cases will wrongfully limit the maximum saving to 40% based on the experimental data obtained in this chapter. To cater for the inclusion of no-load costs, cost-prioritized droop schemes are therefore proposed in the next chapter.

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- [2]. **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Cost-Based droop scheme with lower generation costs for microgrids," *In Proceedings of the 5th Annual International Energy Conversion Congress and Exhibition, ECCE Asia*, Melbourne, pp.339-343, June 2013,
- [3]. **I. U. Nutkani**, P. C. Loh, W. Peng, F. Blaabjerg, "Autonomous droop scheme with reduced generation cost," *Trans. of Indus. Elect.*, [IEEE Explorer DOI: 10.1109/TIE.2014.2314056](https://doi.org/10.1109/TIE.2014.2314056)
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Chapter 4

Cost-Prioritized Droop Schemes for Standalone Microgrids

4.1 Introduction

This chapter presents cost-prioritized droop schemes, whose power dispatch priorities and droop curve orientation are tuned based on the DG generation cost characteristics. The aim is to reduce the overall generation cost of the considered microgrid. Compared with the schemes presented in Chapter 3, the cost-prioritized schemes consider the no-load costs and their variations among the DGs. Such considerations are needed for cases, where DGs can be turned off, which in the present context, refer to those that are more expensive under light load conditions. By defining the dispatch priorities in this way with the less costly DGs producing more, a significant saving in cost can promptly be arrived for the considered microgrid, whose DGs can be turned off, where necessary. The proposed schemes have been tested in experiments, whose results obtained from different microgrid configurations and load conditions have been included in a later section of the chapter.

4.2 Cost-Prioritized Droop Scheme

As reviewed earlier, the traditional droop schemes for parallel DGs control usually aim for proportional power sharing tuned according to their power ratings. This works fine

for the DGs with close similarity, but not really for an autonomous rural or islanded microgrid, where different types of DGs may exist, and are difficult to manage centrally because of their distances. To better adapt to this non-uniformity, an alternative viewpoint based on reducing the total generation cost of the microgrid has been discussed in the earlier chapters. The four different cost-based droops schemes have been presented and their benefits in terms of generation cost saving in standalone microgrid have been demonstrated. In all aforementioned proposed schemes, the no-load (NL) cost has been ignored while making power sharing decision due to which maximum achievable cost saving in a microgrid is limited to a certain percentage. In earlier proposed schemes it was supposed that all the droop controlled DGs remain ON all the time. However, it shall not be always the case; for example, under light load condition it is more appropriate to turn-off some of the expensive/reserve DGs to save the no-load cost. Under such circumstances, the complete cost characteristics including the no-load (NL) and full-load (FL) cost variation of DGs shall be dually considered.

To address the raised concerns, two alternative cost-prioritized droop schemes are developed. The schemes operate by tuning the dispatch priorities of the DGs and curve shapes of their resulting active power versus frequency and reactive power versus voltage plots. The objective aimed is to arrive at a steady-state power sharing among the DGs that will burden the microgrid with a lower total generation cost (TGC) than the traditional and earlier proposed droop schemes.

4.2.1 Generation Cost Curves of DGs

The earlier derived quadratic cost-functions equation (3-1) and (3-9) are used for DG 1 and DG 2 and equation (3-8) is used for DG 3 to draw the generation cost curves for the example microgrid shown in Fig. 4-1. For illustration, the quadratic cost curves are

shown in Fig. 4-2(a) and (b). These cost curves are plotted as $C'_{P,x}(P_x)$ versus P'_x and $C'_{Q,x}(Q_x)$ versus Q'_x , whose definitions are provided as follows.

$$C'_{Y,x}(Y_x) = \frac{C_{Y,x}(Y_x)}{Y_{x,max}}; \quad Y'_x = \frac{Y_x}{Y_{x,max}}; \quad Y = P \text{ or } Q \quad (4-1)$$

As mentioned in Chapter 3, applying (4-1) is necessary to avoid the DG ratings from distorting the cost consideration. To illustrate, a DG producing its rated power at a certain cost is assumed. This DG is definitely not more costly than two half-rated DGs producing the same power at half the cost each. They are in fact equally costly, which can clearly be seen upon dividing their costs and actual powers generated by their individual rated (or maximum) powers. The normalized cost curves obtained can subsequently be used by the cost-prioritized schemes discussed from the next section onwards.

Fig. 4-1. Microgrid configuration “T” with three DGs

Fig. 4-2. Microgrid three DGs (a) active and (b) reactive power generation cost curves

4.2.2 Methodology

Two cost-prioritized droop schemes are proposed, whose details are elaborated as follows.

4.2.2.1 Linear Technique

Existing droop schemes are almost always developed from two linear droop relationships linking frequency f_x with active power P_x and terminal voltage V_x with reactive power Q_x , whose mathematical elaboration is given in (4-2) and (4-3).

$$f_x = f_{max} - m_x P_x ; \quad m_x = \frac{f_{max} - f_{min}}{P_{x,max}} \quad (4-2)$$

$$V_x = V_{max} - n_x Q_x ; \quad n_x = \frac{V_{max} - V_{min}}{Q_{x,max}} \quad (4-3)$$

Depending on the number of DGs considered in microgrid, there can then be a number of different droop lines for each relationship. These droop lines will however usually converge together if they use the same frequency & voltage ranges ($f_{min} \leq f_x \leq f_{max}$) and $V_{min} \leq V_x \leq V_{max}$), and are normalized by their respective DG maximum rated

powers like in (4-1). An illustration of a few active and reactive power droop lines converged together is shown in Fig. 4-3(a) and (b).

Taking Fig. 4-3(a) as an example, in the steady state, the normalized droop lines will have a single common frequency ($f_1 = f_2 = \dots = f$), and hence a single normalized active power ($P'_1 = P'_2 = \dots = P'$). The actual active power given by $P_x = P' \times P_{x,max}$ will then be proportional to the DG rating $P_{x,max}$ since P' is a constant for all DGs. The same principles can be applied to reactive power sharing, but in the steady state, V_x will usually not converge to a common value due to the presence of system mismatches as discussed previously. Sharing of reactive power is therefore not as accurate, as per most existing droop schemes, unless voltage drop through feeder is same or feeder impedance compensation technique is introduced.

Although the droop lines in Fig. 4-3(a) and (b) work fine, their responses have not been economically prioritized since the DG generation costs have not been considered. They might hence not be comprehensive enough for autonomous rural or islanded microgrids, where centralized system for managing the different types of DGs does not exist. To address this concern, a linear modifying technique is proposed, whose required first step is to identify those few parameters in (4-4) from the cost curves shown in Fig. 4-2(a) and (b).

$$C'_{Y,min}(0) = \min \left(C'_{Y,1}(0), C'_{Y,2}(0), \dots, C'_{Y,x}(0) \right)$$

$$C'_{Y,max}(0) = \max \left(C'_{Y,1}(0), C'_{Y,2}(0), \dots, C'_{Y,x}(0) \right)$$

$$C'_{Y,min}(Y_{max}) = \min \left(C'_{Y,1}(Y_{1,max}), C'_{Y,2}(Y_{2,max}), \dots, C'_{Y,x}(Y_{x,max}) \right)$$

$$C'_{Y,max}(Y_{max}) = \max \left(C'_{Y,1}(Y_{1,max}), C'_{Y,2}(Y_{2,max}), \dots, C'_{Y,x}(Y_{x,max}) \right); Y = P \text{ or } Q \quad (4-4)$$

Fig. 4-3. Traditional droop lines for (a) active and (b) reactive power when plotted with normalized power axes

Fig. 4-4. Linear cost-prioritized droop lines for (a) active and (b) reactive when plotted with normalized power axes

In (4-4), where $\min()$ and $\max()$ are functions that return the minimum and maximum values of parameters included in the parentheses. Note that besides those presently operating, DGs planned for future expansion can also be included for determining (4-4) so that they can be added when necessary with an eventual TGC saving still guaranteed.

The identified parameters in (4-4) can next be used to “split” the common active droop line in Fig. 4-3(a) into x different lines for the x DGs based on their generation costs.

The suggested mathematical modifications are presented as follows.

Maximum and minimum frequencies of DG x

$$f_{x,max} = f_{max} - \frac{f_{max}-f_{min}}{2} \times \frac{C'_{P,x}(0)-C'_{P,min}(0)}{C'_{P,max}(0)-C'_{P,min}(0)} \quad (4-5)$$

$$f_{x,min} = \frac{(f_{max}+f_{min})}{2} - \frac{f_{max}-f_{min}}{2} \times \frac{C'_{P,x}(P_{x,max})-C'_{P,min}(P_{max})}{C'_{P,max}(P_{max})-C'_{P,min}(P_{max})} \quad (4-6)$$

Maximum and minimum voltages of DG x

$$V_{x,max} = V_{max} - \frac{V_{max}-V_{min}}{2} \times \frac{C'_{Q,x}(0)-C'_{Q,min}(0)}{C'_{Q,max}(0)-C'_{Q,min}(0)} \quad (4-7)$$

$$V_{x,min} = \frac{(V_{max}+V_{min})}{2} - \frac{V_{max}-V_{min}}{2} \times \frac{C'_{Q,x}(Q_{x,max})-C'_{Q,min}(Q_{max})}{C'_{Q,max}(Q_{max})-C'_{Q,min}(Q_{max})} \quad (4-8)$$

When implemented, (4-5) and (4-7) cause the maximum permitted frequencies and voltages of the DGs to be reoriented within the range of $0.5(\vartheta_{max} + \vartheta_{min}) \leq \vartheta_{x,max} \leq \vartheta_{max}$, where $\vartheta = f$ or V , depending on their generation costs. A similar reorientation of the minimum permitted frequencies and voltages within the range of $\vartheta_{min} \leq \vartheta_{x,min} \leq 0.5(\vartheta_{max} + \vartheta_{min})$ is triggered by (4-6) and (4-8). When combined together, the four equations lead to those “split” active and reactive droop lines shown in Fig. 4-4(a) and (b) for the three considered DGs. The pattern observed from the two figures is the placement of DG with the lowest generation cost at the top and the placement of DG with the highest cost at the bottom. At a fixed steady-state frequency and an approximately equalized voltage (represented by horizontal lines in Fig. 4-4(a) and (b)), the least costly DG will then produce more active and reactive powers. That causes the TGC of the overall microgrid to drop, as compared to the traditional droop schemes. For example, at operating point (1) in Fig. 4-4(a), the least costlier DG 3 can meet the load demand in the considered microgrid therefore comparatively expensive DG 1 and DG 2

can be turned-off to save the no-load losses and hence the saving. At another instant, load increases in a microgrid, let's say at operating point (2) in Fig. 4-4(a), DG 3 being least costlier DG saturates by producing $\sim P_{3,max}$, whereas, the remaining load demand is shared by DG 1 and DG 2.

Also noted in Fig. 4-4(a) and (b) are some overlapping generating regions located between $\vartheta_{(x+1),min}$ and $\vartheta_{x,max}$, where $\vartheta = f$ or V . One of them is between $f_{3,min}$ and $f_{2,max}$, where DG 2 is demanded to start its active power generation before DG3 saturates. With DG 2 generating, a larger load increase can promptly be met, which otherwise is not possible since DG 3 is about to saturate, and hence cannot meet the load increase by itself. This overlapping region therefore provides a mechanism for the load to continue increasing, if necessary. With the modified frequencies and voltages included, the eventual droop expressions used for control are given by (4-9) and (4-10). These expressions are undeniably the same as those found in traditional droop schemes, but with different frequency and voltage limits introduced to account for the different DG generation costs.

$$f_x^* = f_{x,max} - m_{x,L} P_x; \quad m_{x,L} = \frac{f_{x,max} - f_{x,min}}{P_{x,max}} \quad (4-9)$$

$$V_x^* = V_{x,max} - n_{x,L} Q_x; \quad n_{x,L} = \frac{V_{x,max} - V_{x,min}}{Q_{x,max}} \quad (4-10)$$

4.2.2.2 Nonlinear Technique

The cost-prioritized linear droop scheme discussed above is no doubt simple and effective with only two constant droop coefficients $m_{x,L}$ and $n_{x,L}$ computed per DG. However, it considers only the minimum and maximum costs of each DG read from Fig. 4-2(a) and Fig. 4-2 (b). Variations between these ends are mostly ignored, which will certainly create some amount of inaccuracy for some cases. For example, if two

DGs in a microgrid have the same minimum and maximum costs, and if the linear technique is applied, they will always share powers equally even if their cost variations between the two limits are different. This is certainly not intended, and can be improved by varying the gradients of the cost-prioritized expressions according to the different generation cost curves. The resulting expressions are given by (4-11) and (4-12).

$$f_x^* = f_{x,max} - m_{x,N} P_x ;$$

$$m_{x,N} = \frac{f_{x,max} - f_{x,min}}{P_{x,max}} \times \frac{C'_{P,x}(P_x) - C'_{P,x}(0)}{C'_{P,x}(P_{x,max}) - C'_{P,x}(0)} = m_{x,L} \times \frac{C'_{P,x}(P_x) - C'_{P,x}(0)}{C'_{P,x}(P_{x,max}) - C'_{P,x}(0)} \quad (4-11)$$

$$V_x^* = V_{x,max} - n_{x,N} * Q_x ;$$

$$n_{x,N} = \frac{V_{x,max} - V_{x,min}}{Q_{x,max}} \times \frac{C'_{Q,x}(Q_x) - C'_{Q,x}(0)}{C'_{Q,x}(Q_{x,max}) - C'_{Q,x}(0)} = m_{x,L} \times \frac{C'_{Q,x}(Q_x) - C'_{Q,x}(0)}{C'_{Q,x}(Q_{x,max}) - C'_{Q,x}(0)} \quad (4-12)$$

In the two expressions, the cost-function $C'_{Y,x}(Y_x)$ ($Y = P$ or Q) is not used alone to modify the droop coefficients. A term $C'_{Y,x}(Y_x = 0)$ has been subtracted from it, which is necessary since this term represents the fixed cost incurred by operating the DG, and hence does not include any information about variation. The subtracted term $C'_{Y,x}(Y_x) - C'_{Y,x}(Y_x = 0)$ must further be divided by $C'_{Y,x}(Y_{x,max})$, which is mathematically necessary to retain the dimension of the gradient as Hz / kW. The resulting nonlinear droop curves are shown in Fig. 4-5(a) and (b), which obviously have variable slopes.

Although the nonlinear scheme should distinguish the DGs better, its usage should generally be avoided if the linear technique works fine because of a number of reasons. The first reason is linked to its variable slopes, which although distinguish the DGs better, can at times be too gentle (very small gradients) close to $Y_x = 0$ or too steep close to $Y_x = Y_{x,max}$. Although gentle slopes ensure better regulation, they cannot accurately represent the intended power sharing, and can hence lead to an unintended

higher cost than the linear technique. Sleep slopes, on the other hand, can cause undesirable oscillation or stability problems, which can be resolved by limiting the maximum permitted slopes. This might again limit the accuracy of the intended sharing, whose outcome is a higher cost than the linear technique. Because of these constraints, the linear technique should generally be chosen for most cases.

Fig. 4-5. Nonlinear cost-prioritized droop lines for (a) active and (b) reactive power when plotted with normalized power axes

4.2.3 Experimental Setup

To verify the cost-prioritized droop schemes presented above, the experimental setup described in Chapter 3, Subsection 3.4.4. was used to implement the microgrid shown in Fig. 4-1. The microgrid topology and control realized with DG converter is shown in Fig. 4-6. The DGs were programmed to have a maximum power of 1 kW each at a power factor of 0.8, unless otherwise mentioned. The frequency and voltage ranges chosen for the microgrid were $f_{min} = 49Hz \leq f_x \leq f_{max} = 51Hz$ and $V_{min} = 0.95p.u. \leq V_x \leq V_{max} = 1.05p.u.$ (base voltage = 190V Line-RMS).

Fig. 4-6. Experimental microgrid for testing the cost-prioritized droop schemes

4.2.4 Experimental Results

4.2.4.1 Configuration I

The active power generation cost curves chosen are shown in Fig. 4-7(a) for its three DGs considered in microgrid configuration I (parameters of the cost curves can be found in Section 3.4.3). Relevant minimum and maximum values indicated on the cost curves were then used to derive the active droop lines shown in Fig. 4-7(b) and (c) with their respective minimum and maximum values also indicated. The reactive power sharing was set analogous to active power therefore the values shown in active power cost curves are used to define the reactive droop line shown in Fig. 4-7(c). Based on these derived droop lines, the dispatch priorities of the three DGs are identified as follow:

- $f_{3,max} = 51.00\text{Hz}$, $V_{3,max} = 1.05\text{p.u.} \Rightarrow$ DG3 first to generate when the load is light.
- $f_{2,max} = 50.53\text{Hz}$, $V_{2,max} = 1.027\text{p.u.} \Rightarrow$ DG2 second to generate when the load increases.
- $f_{1,max} = 50.00\text{Hz}$, $V_{1,max} = 1\text{p.u.} \Rightarrow$ DG1 third to generate when the load is high.

Fig. 4-7. Microgrid configuration “I” three DGs (a) cost curves, linear cost-prioritized (b) active and (c) reactive power droop lines

Experiments were then performed for five different load conditions set at 15%, 30%, 45%, 60% and 75% of the total generation capacity of the microgrid. Results obtained are shown in Fig. 4-8 and Fig. 4-9, where the former clearly shows that only the least costly DG 3 with the highest priority is operating at 15% load interval($t=0$ to 50sec).

(a)

(b)

(c)

(d)

Fig. 4-8. Microgrid configuration “T” (a) active and (b) reactive power sharing, (c) frequency and (d) voltage variations during five different loading intervals

(a)

(b)

Fig. 4-9. Microgric configuration “I” TGC with (a) linear and (b) nonlinear cost-prioritized droop schemes when compared with the traditional droop scheme

As the load progressively increases, DG 2 is the next to operate at $t = 50$ s, before the most costly DG 1 with the lowest dispatch priority turns on at $t = 150$ s.

When in the steady state, the derived droop lines show that the least costly DG 3 will generate more, followed by DG 2 and then DG 1. This expectation is confirmed by the active and reactive power sharing plots shown in Fig. 4-8 (a) and (b) for the five step-changed load conditions. Corresponding frequency and voltage variations are also shown in Fig. 4-8(c) and (d). With this intended power sharing, the linear cost-prioritized droop scheme leads to a lower TGC for the microgrid, as seen from Fig. 4-9(a), where it is compared with the traditional droop scheme. For comparison, TGC obtained with the nonlinear technique is also shown in Fig. 4-9(b), which because of the constraints mentioned earlier, is higher than that of the linear technique, but still lower than the traditional scheme.

4.2.4.2 Configuration II

The microgrid configuration was subsequently modified to include a fourth DG, as shown in Fig. 4-10 for evaluating the flexibility of the schemes when subjected to changes. The earlier droop parameters computed for (4-5) to (4-10) were however kept unchanged for checking the system effectiveness even when not re-tuned. The new cost functions and cost-prioritized droop lines for the four DGs are shown in Fig. 4-11(a) and (b). The reactive droop lines are not shown because like observed in Fig. 4-8(b), they are the same as the active droop lines. With these modified settings, Fig. 4-12(a) shows the obtained results with the least costly DG 3 again generating the most, and most costly DG 1 generating the least. This leads to the saving in TGC shown in Fig. 4-12(b) for the cost-prioritized microgrid.

Fig. 4-10. Microgrid configuration "II" with three DGs

(a)

(b)

Fig. 4-11. Microgrid configuration “II” four DGs (a) cost curves and (b) linear cost-prioritized active power droop lines

(a)

(b)

Fig. 4-12. Microgrid configuration “II” (a) active power sharing and (b) TGC with linear cost-prioritized droop when compared with the traditional droop scheme

TABLE 4-1: TGC savings achieved by the linear cost-prioritized scheme when compared to the traditional scheme

Loading*	Configuration-I		Configuration-II	
	DGs in Operation	TGC Saving	DGs in Operation	TGC Saving
15%	3	88%	3 and 4	83%
30%	2 and 3	58%	2, 3 and 4	50%
45%	2 and 3	54%	2, 3 and 4	47%
60%	1, 2 and 3	15%	1, 2, 3 and 4	16%
75%	1, 2 and 3	12%	1, 2, 3 and 4	14%

*Percentage of microgrid total capacity

For comprehensiveness, the savings obtained from the tests are summarized in TABLE 4-1. From the values, it is clear that the amount saved is more prominent at light load, during which the least costly DG3 has not yet saturated, and can hence supply more to bring down the TGC of the microgrid. This is however not the case at heavy load, during which DG3 and other DGs with lower costs have saturated, leaving only the more costly DGs to generate. The savings obtained are thus anticipated to be lesser.

4.3 Stability and Extended Applications of Cost-Prioritized Droop Schemes

4.3.1 Stability of Cost-Prioritized Droop Schemes

Like in Chapter 3, droop gains of the traditional and cost-prioritized droop schemes are compared using their finite matrices provided in (4-13) and (4-14). Their corresponding

droop gains are compared in (4-15). Clearly, droop gain of any cost-prioritized DG " m_L " will always be smaller than the traditional droop gain " m ", since all cost-prioritized DGs are operating in narrower frequency and voltage ranges, as shown in Fig. 4-4. These ranges are always kept within defined limits ($\Delta V_{mg} = V_{max} - V_{min}$; $\Delta f_{mg} = f_{max} - f_{min}$) as long as stability is ensured by choosing the droop gains appropriately. A stable cost-prioritized microgrid has indeed been verified earlier in experiment for different load conditions.

Finite matrix of the traditional droop scheme:

$$A_{DG} = \begin{bmatrix} 0 & -m & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & \frac{-n k_{vp} k_{ip}}{L_f} & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1 - k_{vp} k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & 0 & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1 - k_{vp} k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \quad (4-13)$$

Finite matrix of the cost-prioritized droop scheme:

$$A_{DG} = \begin{bmatrix} 0 & -m_L & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & 0 & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1 - k_{vp} k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & \frac{-n_L k_{vp} k_{ip}}{L_f} & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1 - k_{vp} k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \quad (4-14)$$

Droop gains of the two schemes can be compared by writing the following inequality.

$$|-m_L| \leq |-m| \quad (4-15)$$

4.3.2 Cost-Prioritized Droop Schemes for LV Resistive Network

Like mentioned earlier in Chapter 3, the proposed cost-prioritized droop schemes can be used with a resistive microgrid after applying a decoupling technique like adding inductive virtual impedances. A diagram illustrating the addition is shown in Fig. 4-13.

Fig. 4-13. Cost-prioritized droop controller with virtual impedance loop

4.4 Conclusions

Two cost-prioritized droop schemes have been proposed, which when implemented, lead to a steady-state power sharing that will reduce the TGC of the considered microgrid. This goal has not been achieved by other traditional droop schemes, whose common objective has always been to achieve proportional power sharing based on the DG ratings. Unlike the droop schemes discussed in Chapter 3 too, the cost-prioritized droop schemes presented here has a greater saving in cost, especially under light load conditions during which the more expensive DGs can be turned-off. The proposed

schemes are therefore more suitable for specific microgrids, whose DGs having different no-load costs can freely be turned off. Effectiveness of the schemes has already been verified in experiments for two different microgrid configurations at different load levels.

4.5 Acknowledgement

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- [1] **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Cost-prioritized droop schemes for autonomous microgrids," *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2013, Denver, CO, pp.1021-1025, Sep. 2013.
- [2] **I. U. Nutkani**, P. C. Loh, W. Peng, F. Blaabjerg, "Cost-prioritized droop schemes for autonomous microgrids," *IEEE Trans in Power Electron.* [IEEE Explorer DOI: 10.1109/TPEL.2014.2313605](https://doi.org/10.1109/TPEL.2014.2313605)

Chapter 5

Distributed Droop Scheme for Interlinked AC Microgrids

5.1 Introduction

In the earlier chapters, a total of six different distributed droop schemes have been proposed for standalone microgrids. The focus is now directed at interlinked microgrids, whose power flows through interlinking converters must be controlled properly. For that, an interlinking droop scheme has been proposed in this chapter with its subsequent two variants discussed in the next chapter. Upon applied to the interlinking converters, the microgrids share power efficiently, while allowing their individual voltages and frequencies to be set differently. To test its performance, an experimental system has been built, whose details are described in a later section of this chapter. Results obtained match closely with expectations, hence confirming the practicality of the scheme presented in this chapter.

5.2 Power Flow Management among Interlinked AC Microgrids

The formed standalone microgrids are, by nature, independent entities, whose operating voltages and frequencies can be set to suit their respective DGs and load characteristics. The microgrids can then operate in isolation or tied to the utility grid. Among themselves, there can also be intertied to reinforce their reserve sharing, security and

energy trading. Intertying of microgrids and its related power flow issues are hence not yet thoroughly investigated especially for cases where only local variables can be measured due to the dispersed nature of DGs in microgrid.

These issues are now addressed by properly extending the droop scheme from a single ac microgrid to a few interlinked microgrids operating at their own preferred voltages and frequencies. Application of droop scheme to interlinked microgrids is more challenging because of a number of related operating issues. The first is their usual demand for autonomous control without fast communication link because of their widely dispersed source placements. The second is their more stringent supply-demand balance enforced within each comparably sized microgrid, which surely is more complex than the previously reviewed control in Chapter 2 for standalone microgrids. Besides harmonizing different operating voltages and frequencies, the control schemes used with the interlinking power converters should be designed with reactive power support and active power transfer among the microgrids. Methodology to address the issues raised in above para and the general requirements identified in Chapter 2, is given in the following sections.

5.2.1 Methodology

A simple example of interlinked microgrids is shown in Fig. 5-1, where two microgrids *A* and *B* are intertied by a few interlinking converters. These interlinking converters are usually of the back-to-back ac-dc-ac type with an intermediate dc-link stage. Their functionality is to harmonize different operating conditions of the microgrids, which in Fig. 5-1, are represented by different indicated frequencies. Although voltages in the figure are assumed to be the same for both microgrids, they can generally be set to different values, if intended, without affecting the proper functioning of the proposed

droop scheme. The interlinked microgrids can then either operate independently as an island or tied to the utility grid. The latter can be realized by another string of interlinking converters if the operating voltages and frequencies of the microgrids and utility grid are different. Alternatively, static switch or breaker can be used like shown in Fig. 5-1 between microgrid *B* and the utility grid. Both entities are assumed to have the same operating conditions with only minor synchronization needed before closing the static switch.

Although the power management scheme for interlinked microgrid is explained with the example of two microgrids tied together but concept in general could be extended for more than one interlinking converter and more than two interlinked microgrids. The proposed droop scheme for the interlinking converters is given the following section followed by the review of droop scheme used for DGs in each microgrid.

5.2.1.1 Droop Scheme for Single Microgrid

The droop scheme underlying principles are related to the simplified active (P) and reactive (Q) power flow expressions listed in Chapter 2, Sections 2.2.1. The same linear active and reactive power variations can be introduced to microgrid DGs to have the droop characteristics shown on the right of Fig. 5-2 and Fig. 5-3 for microgrid “*B*” quoted as an example. For “*x*” microgrid with “*y*” DGs in parallel, their linear gradients, also known as droop coefficients, can then be computed using (5-1) and (5-3), where $f_{x,max}$, $f_{x,min}$, $V_{x,max}$ and $V_{x,min}$ are the common maximum and minimum frequencies and voltages assumed by the DGs.

Fig. 5-1. Illustration of intertied microgrids.

If maximum active power $P_{xy,max}$ and reactive power $Q_{xy,max}$ are further set proportional to the DG kVA ratings (5-1) and (5-3) expand to (5-2) and (5-4), which must be satisfied to obtain proportional power sharing among the DGs based on their respective kVA ratings.

$$f_{xy}^* = m_{xy}P_{xy} + f_{x,max}; \quad m_{xy} = \frac{f_{x,min} - f_{x,max}}{P_{xy,max}} < 0 \quad (5-1)$$

$$m_{x1} * S_{x1,max} = m_{x2} * S_{x2,max} = m_{x3} * S_{x3,max} = \dots = m_{xy} * S_{xy,max} \quad (5-2)$$

$$V_{xy}^* = n_{xy}Q_{xy} + V_{x,max}; \quad n_{xy} = \frac{V_{x,min} - V_{x,max}}{Q_{xy,max}} < 0 \quad (5-3)$$

$$n_{x1} * S_{x1,max} = n_{x2} * S_{x2,max} = n_{x3} * S_{x3,max} = \dots = n_{xy} * S_{xy,max} \quad (5-4)$$

In (5-1) and (5-3), m_{xy} and n_{xy} are the active and reactive power droop coefficients, respectively. At times, (5-4) might not be sufficient for guaranteeing proportional reactive power sharing among the generating sources because of different feeder voltage drops and other parameter mismatches. Modifications to compensate for the mismatches have already been reviewed in Chapter 2, and will hence not be discussed while discussing the autonomous power flow control among multiple microgrids.

Fig. 5-2. Active power droop characteristics of microgrids and interlinking converters

Fig. 5-3. Reactive power droop characteristics of microgrids and interlinking converters

5.2.1.2 Droop Scheme for Interlinking Converters

When microgrids are tied together like in Fig. 5-1, there are some general features that they can jointly demonstrate, as identified in Chapter 2, Section 2.5. These features are explained below for the proposed scheme in this section, whose purposes are mainly to enhance the overall system reliability, efficiency and performance.

- *Active power flow from under-loaded to overloaded microgrid for reinforcement.*

At any instant in the steady state, active power balance must be maintained at the two ends of the interlinking converters to keep their common dc-link voltage V_{dc} stable.

- *Reactive power reinforcement provided by interlinking converters upon requested.* Reactive power reinforcement needs not be balanced at the two ends of the interlinking converters, and can hence be independently performed.
- *Priority tuning between active and reactive power generations.* Depending on the load types and their associated power factors, priority to supply active or reactive power by the interlinking converters can be set accordingly.
- *Unnecessary operating time and losses of interlinking converters can be minimized.* This happens when the intertied microgrids are either all under-loaded or heavily overloaded. The former means the microgrids do not need additional generation, while the latter means they are close to their ratings, and hence do not have additional generating capacities for sharing.

The above-mentioned features and requirements can be fulfilled by the following proposed scheme for the interlinking converters. The scheme is autonomous with only locally measured voltages and frequencies involved.

5.2.1.3 Islanded Mode

To isolate the interlinked microgrids, the static switch connected to the utility in Fig. 5-1 must be opened. With no utility grid, supply-demand balancing within the microgrids is generally more stringent since any surplus cannot be channeled to the grid and any deficit cannot be replenished from it. It is hence necessary for the interlinking converters to measure generating conditions of the two microgrids in Fig. 5-1, before deciding on the amount of power to transfer between them. The eventual goal is to arrive at a supply-demand balance for the intertied microgrids in the steady state. Before proceeding further, it is helpful to clarify that this method of interlinking control is

different from that explained in Subsection 5.2.1.1 for a single DG in a single microgrid. The former requires measurements from two microgrids before appropriately combining them to produce the necessary interlinking control action, which to date has not been reported in the literature. The latter, on the other hand, measures operating conditions within a single microgrid with no interlinking intelligence needed. It is hence much simpler, and no doubt has already been well-established. Returning to the measurement of microgrid generating conditions, its frequency and voltage can be measured instead because of those “cumulative” microgrid droop lines shown in Fig. 5-2 and Fig. 5-3. It is hence important for each interlinking converter to have its own phase-locked-loop (PLL) for extracting frequency and magnitude information from its measured terminal voltages. In addition to that, it should be mentioned that the term “cumulative” has been used with the microgrid droop characteristics to reflect the fact that the interlinking converters cannot see the individual DG details of the microgrids at their terminals. Only the summed responses of the microgrids are visible to the interlinking converters at their terminals. A set of power request curves can next be defined for the interlinking converters, whose pictorial representations are shown in the middle of Fig. 5-2 and Fig. 5-3. Power request (both active and reactive) here is defined as the anticipated positive power demanded by microgrid “ x ” ($x = A$ or B) to flow into it when it is either overloaded or heavily overloaded. The request can certainly be negative with power demanded to flow out of microgrid “ x ” when it is under-loaded, but for this paper, it is simply set to zero without compromising the effectiveness of the scheme. Beginning now with the active droop requests shown in Fig. 5-2 and notated as $P'_{x,IC}$, their representative equations and defined ranges can be expressed as:

$$P'_{x,IC} = \begin{cases} 0, & f_{x,OL} < f_x \leq f_{x,max} \text{ (Underloaded)} \\ m_{x,IC}(f_x - f_{x,OL}), & f_{x,HOL} < f_x \leq f_{x,OL} \text{ (Overloaded)} \\ P_{x,IC,max}, & f_{x,min} \leq f_x \leq f_{x,HOL} \text{ (Heavily Overloaded)} \end{cases} ; x = A \text{ or } B$$

$$m_{x,IC} = \frac{P_{x,IC,max}}{f_{x,HOL} - f_{x,OL}} \quad (5-5)$$

In (5-5), $m_{x,IC}$ is the droop coefficient for the active power request, and subscripts OL and HOL are for notating thresholds below which the microgrids are considered overloaded and heavily overloaded, respectively. Also included in (5-5) is the variable $P_{x,IC,max}$ for representing the maximum active power that can be requested, which based on the earlier definition for power request, is always positive. This maximum, together with the concepts brought forward by (5-5), is better explained with an example, but before addressing it, it is important to clarify that active power requested $P'_{x,IC}$ in (5-5) might not be the actual active power $P^*_{x,IC}$ produced by interlinking converter “x”. The requested active power $P'_{x,IC}$ is simply a value that interlinking converter “x” would expect microgrid “x” to request from it based on the detected frequency f_x . Requested values from both microgrids must promptly be considered before interlinking converter “x” and its back-to-back companion know how much actual active power $P^*_{x,IC}$ to inject to the microgrids.

The actual active power $P^*_{x,IC}$ can in fact be computed from (5-6), which value is positive when power is flowing out of interlinking converter “x”. This notation causes $P^*_{A,IC}$ and $P^*_{B,IC}$ in (5-6) to have equal magnitude but opposite polarity needed to stabilize the dc-link voltage of the interlinking converters. In practice, a small difference ΔP^*_{IC} is also added to account for losses in the converters. Value for ΔP^*_{IC} can automatically be produced by passing error between the dc-link voltage and its reference through a proportional-integral (PI) controller. The obtained ΔP^*_{IC} can then be added to $P^*_{A,IC}$, $P^*_{B,IC}$ or divided between them in order to draw the necessary active power needed to keep the

dc-link voltage constant. Other reasons on why $P_{x,IC}^*$ is formulated like in (5-6) will, as mentioned earlier, be more obvious when describing the example to be followed next.

$$P_{A,IC}^* = -P_{B,IC}^* = \begin{cases} K \times P_{A,IC,max}, & \text{if } K \geq 0 \\ K \times P_{B,IC,max}, & \text{if } K < 0 \end{cases} \quad K = \frac{P'_{A,IC}}{P_{A,IC,max}} - \frac{P'_{B,IC}}{P_{B,IC,max}} \quad (5-6)$$

Assuming the two microgrids shown in Fig. 5-1 are initially not loaded, their frequencies will then be at their respective maximum notated as $f_{x,max}$. Loading in microgrid “A” is subsequently increased, followed promptly by its source generation to meet the load demand. From its source droop line shown on the left of Fig. 5-2, frequency f_A of microgrid “A” will then fall. The interlinking converters, after sensing f_A and f_B ($= f_{B,max}$ since not yet loaded), will compare them with those ranges defined in (5-5). If f_A remains in the under-loaded range, powers requested by the two microgrids are estimated as $P'_{A,IC} = P'_{B,IC} = 0$ based on (5-5) or the interlinking droop characteristics shown in the middle of Fig. 5-2. Since the microgrids are not asking for additional active power, the actual active power transferred by the interlinking converters should be zero, which is in agreement with the result obtained from (5-6). The requested active power $P_{A,IC}$ will only be non-zero when loading in microgrid “A” is further increased, pulling f_A into the overloaded range. Its value eventually saturates at $P_{A,IC,max}$ when f_A enters the heavily overloaded range. Since microgrid “B” is still not loaded, it has the capacity to generate active power requested by microgrid “A”, but only up to its rated capacity notated as $P_{B,max}$. The maximum active powers that microgrids “A” and “B” can request are therefore capped by (6-7), and the actual active power transferred is set as $P_{A,IC}^* = -P_{B,IC}^* = P'_{A,IC}$ based on the described example. This is indeed the outcome obtained from (5-6).

$$P_{A,IC,max} \leq P_{B,max} \quad \text{and} \quad P_{B,IC,max} \leq P_{A,max} \quad (5-7)$$

Assuming next that loading of microgrid “B” is gradually increased, causing its source generation to rise and its frequency f_B to fall. Upon f_B entering the overloaded range, requested power $P'_{B,IC}$ starts to increase above zero. Since $P'_{A,IC}$ and $P'_{B,IC}$ are both non-zero, they must be compared. If $P'_{A,IC} > P'_{B,IC}$, microgrid “A” is loaded more, and should hence be helped with actual active power flowing into it ($P_{A,IC}^* = -P_{B,IC}^* =$ positive). The flow should reverse when $P'_{B,IC} > P'_{A,IC}$ (or when $P_{A,IC}^* = -P_{B,IC}^* =$ negative). These requirements are again in line with result obtained from (5-6). If loading of microgrid “B” is further increased until f_B enters the heavily overloaded range, both requested powers would be at their maximum, expressed as $P'_{A,IC} = P_{A,IC,max}$ and $P'_{B,IC} = P_{B,IC,max}$. Since both microgrids are heavily overloaded, they do not have excess generating capacities for sharing. The actual active power transferred should hence decrease to zero, which is again accounted by (5-6). Other loading sequences can similarly be tried with (5-5), (5-6) and (5-7) still giving the anticipated results. They are hence appropriate for controlling the active power flow of the interlinking converters in an autonomous manner.

To further strengthen confidence with (5-5), (5-6) and (5-7), a simple case to show how they can be applied is described here, where it is assumed that the two microgrids can produce the same maximum power P_{max} . Other relevant maximum power values mentioned earlier can hence be set as $P_{x,IC,max} = P_{x,max} = P_{max}$ ($x = A$ or B). It can next be assumed that the microgrids are loaded such that their requested powers are related by $P'_{A,IC} = 1.5 P'_{B,IC}$. Substituting into (5-6) then gives rise to $K = \frac{0.5 P'_{B,IC}}{P_{max}}$ and $P_{A,IC}^* = -P_{B,IC}^* = 0.5 P'_{B,IC}$. The latter simply means that the interlinking converters must transfer $0.5 P'_{B,IC}$ from microgrid “B” to assist the more overloaded condition in microgrid “A”, as intended, hence proving the effectiveness of the proposed scheme.

Apart from active power flow, the interlinking converters can provide reactive power support to the microgrids, when requested. Unlike active power though, reactive powers at the terminals of the two interlinking converters need not be balanced. They can hence be independently controlled using the interlinking reactive power droop characteristic drawn in Fig. 5-3 for interlinking converter “B”. The same reactive power droop characteristic with different axial values can be used for interlinking converter “A”.

Collectively, they can be represented by the following common mathematical expression.

$$Q_{x,IC}^* = \begin{cases} 0, & V_{x,OL} < V_x \leq V_{x,max} \text{ (Underloaded)} \\ n_{x,IC}(V_x - V_{x,OL}), & V_{x,HOL} < V_x \leq V_{x,OL} \text{ (Overloaded)} \\ Q_{x,IC,max}, & V_{x,min} \leq V_x \leq V_{x,HOL} \text{ (Heavily Overloaded)} \end{cases} ; x = A \text{ or } B$$

$$n_{x,IC} = \frac{Q_{x,IC,max}}{V_{x,HOL} - V_{x,OL}} \quad (5-8)$$

In (5-8), $n_{x,IC}$ is the interlinking reactive power droop coefficient. Their common operating principles are similar to those of the active power request droop characteristics represented by (5-5). However, unlike (5-5), the value obtained from (5-8) is already the actual reactive power $Q_{x,IC}^*$ produced by interlinking converter “x” for microgrid “x”. No further processing like in (5-6) is needed since reactive power balance is unnecessary. Modification to the maximum reactive power $Q_{x,IC,max}$ that interlinking converter “x” can supply is however needed to account for the fixed converter kVA rating $S_{x,IC,max}$ and its varying actual active power $P_{x,IC}^*$ transferred. This can be done according to (5-9), whose resulting variation is better shown by those dashed lines drawn in Fig. 5-3.

$$Q_{x,IC,max} = \sqrt{(S_{x,IC,rated})^2 - (P_{x,IC}^*)^2} \quad (5-9)$$

The combined power expression produced by the interlinking converters can hence be written as:

$$S_{x,IC}^* = P_{x,IC}^* + jQ_{x,IC}^* \quad (5-10)$$

When $S_{x,IC}^*$ is zero, its associated interlinking converter “x” can be turned off to avoid unnecessary operating losses. It will only be turned on when $S_{x,IC}^* \neq 0$ with microgrid “x” receiving the generated power.

5.2.1.4 Grid-Connected Mode

The interlinked microgrids shown in Fig. 5-1 can be tied to the utility grid by turning on the static switch or breaker placed between them. The same interlinking droop scheme discussed in Subsection 5.2.1.3 can still be used with the interlinking converters without changes. It should however be noted that microgrid “B”, being directly connected to the grid, is now having a fixed frequency f_B and terminal voltage V_B determined by the grid. Any surplus or deficit in power in microgrid “B” will also be balanced by the grid, which in a way, acts like an infinite bus. If the frequency and voltage of microgrid “B” are further designed to be in the under-loaded ranges defined in (5-5) and (5-8), their corresponding requested powers would be $P_{B,IC}' = 0$ and $Q_{B,IC}^* = 0$. The actual active power transferred can hence be simplified from (5-6) to (5-11), while $Q_{B,IC}^*$ is still given by (5-8). It should however be noted that (5-11) is written here for illustration only. The actual implementation is still realized with (5-6), which works fine in both islanded and grid-connected modes.

$$P_{A,IC}^* = -P_{B,IC}^* = -P_{B,IC}' \quad (5-11)$$

5.2.1.5 Other Variations

The above interlinking control description is based on the assumption of P - f and Q - V droop lines used within each microgrid. This is however not always the case. For example, P - V and Q - f droop lines can be used for microgrids, whose line impedances are mostly resistive. Regardless of that, the same interlinking droop principles can still be used, but with V now measured to determine P and f measured to determine Q . The same reasoning can be applied to other hybrid droop relationships used with microgrids having equally prominent resistive and inductive line impedances. The only slight changes expected are the interlinking P and Q commands are now determined by applying the desired interlinking droop relationships to both f and V .

5.2.2 Experimental Setup

A scaled-down version of the interlinked microgrids was assembled in the laboratory for experimental testing, whose schematic is shown in Fig. 5-4 and the hardware setup is same as shown in Fig. 3-5. As shown in the experimental setup schematic, each microgrid was emulated with a DG inverter/converter and a local resistive-inductive load bank for adjusting its loading. The DG inverter/converter is within the considered microgrid, and should hence not be confused with the interlinking converters tying the

Fig. 5-4. Experimental setup for interlinked microgrid

two microgrids together. The DG inverter was controlled using the droop scheme reviewed in Subsection 5.2.1.1 with a usual outer voltage and inner current double-loop controller, reviewed in Chapter 2, Subsection 2.2.3.3. The interlinking converters, on the other hand, were implemented with two six-switch converters sharing a common dc-link as shown in Fig. 5-4. Their common droop scheme was discussed earlier in Subsection 5.2.1.3. Unlike the DG droop scheme which output was a voltage reference, references from the interlinking droop scheme were represented by the power expression given in (5-6) and (5-8). Its tracking controller must therefore be modified accordingly with the outer being the power tracking loop and the inner being the usual voltage-current tracking loop, as shown in Fig. 5-5.

The outer power loop was realized with two proportional-integral (PI) controllers for acting on the active ($P_{x,IC}^* - P_{x,IC}$) and reactive ($Q_{x,IC}^* - Q_{x,IC}$) power errors. Their outputs were the frequency and voltage magnitude commands, which could then be combined to give the three-phase voltage commands (V_a^*, V_b^*, V_c^*) for tracking by the inner voltage-current tracking loop. Including this outer power loop, illustration of the overall control scheme for the interlinking converters could be found in Fig. 5-5. DC-link voltage tracking was not shown in the figure because it had already been accounted by ΔP_{IC}^* explained in Subsection 5.2.1.3.

The ratings and base values used for per-unit (*p.u.*) conversion spelled in TABLE 5-1. Per-unit conversion of powers and voltages was based on the standard formula of actual divided by the chosen base value. Conversion for frequencies was however done differently. Instead of normalizing the frequencies, the conversion shown by (5-12) normalized their variations from their respective mean values. This had the effect of putting them in the same -1 to 1 range for easier comparison of results regardless of what frequency values had been chosen for the microgrids (e.g. 50 and 60Hz, 50 and

400Hz, ... etc). It will also not modify the interlinking droop concepts proposed in this Chapter.

$$f_x(p.u.) = \frac{f_x - \text{Mean}}{0.5 \times \text{Range}} = \frac{2f_x - (f_{x,\max} + f_{x,\min})}{f_{x,\max} - f_{x,\min}} \quad (5-12)$$

Fig. 5-5. Block diagram of interlinking droop scheme

5.2.3 Experimental Results and Analysis

The experiment was performed with five scenarios, which responses had been intentionally slowed down. This was to allow for continuous tracking of operating points on the interlinking active and reactive power request lines, which like all droop schemes, applied only to steady-state responses. Snapshots of the tracking were then shown in appropriate figures to be discussed next.

TABLE 5-1: Ratings and base values for experimental testing

Entities	Ratings
Interlinking Converters	2kVA per converter, 350V (dc-link)
Microgrid “A”	2kVA, 190.5V (ac), 3-phase (60±1)Hz $\Rightarrow f_{A,max} = 61\text{Hz}$, $f_{A,min} = 59\text{Hz}$
Microgrid “B”	2kVA, 190.5V (ac), 3-phase (50±1)Hz $\Rightarrow f_{B,max} = 51\text{Hz}$, $f_{B,min} = 49\text{Hz}$
Parameters	Values
Droop Coefficients	$m_{A,IC} = m_{B,IC} = 1.25$ and $n_{A,IC} = n_{B,IC} = 0$ to 19.2
Base Power	2kVA
Base Voltage	190.5V (ac)

5.2.3.1 Islanded Scenario 1 (Fig. 5-6, and 0 to 100s in Fig. 5-7)

The experiment was started with the interlinking converters not yet activated from 0 to approximately 20s. During this time, the respective load banks in the microgrids were adjusted such that frequency of microgrid “A” was at $f_A = -0.5p.u.$, while that of microgrid “B” was at $f_B = 0.6 p.u.$. They corresponded to those operating points marked as “1a” in Fig. 5-6(a). Microgrid “A” was thus classified as overloaded, while microgrid “B” was considered as under-loaded. The actual active power transferred should hence be from microgrid “B” to “A”, which indeed happened when the interlinking converters were activated from 20s onwards. This transfer of active power caused frequency of microgrid “B” to drop since it was generating the transferred power. Frequency of microgrid “A”, on the other hand, rose since it was receiving the transferred power. Operating points “1a” therefore moved to points “1b” in the steady state, which actual power values read from Fig. 5-7(b) were $P_{A,IC}^* \approx -P_{B,IC}^* = 0.25p.u.$

These values were not exactly equal in magnitude because of a small difference ΔP_{IC}^* needed to keep the dc-link capacitor voltage in Fig. 5-7(e) constant.

Terminal voltages wise, their respective initial values were read from Fig. 5-7(c) as $V_A = V_B = 0.97p.u.$ from 0 to 20s, before activating the interlinking converters. They corresponded to those operating points, also marked with “1a” in Fig. 5-6(b). The two microgrids were thus classified as overloaded, and would hence request for reactive powers from the interlinking converters once they were activated from 20s onwards. This was observed in Fig. 5-7(d), where the common steady-state reactive power injected to each microgrid was read as $Q_{x,IC}^* = 0.2p.u.$ from 20s onwards. With this reactive support provided by the interlinking converters, the microgrid terminal voltages rose slightly to those operating points marked with “1b” in Fig. 5-6(b). These operating points laid on the dashed droop lines, whose common maximum value computed from (5-9) was given by $Q_{x,IC,max} = \sqrt{1^2 - 0.25^2} = 0.96 < 1p.u..$

5.2.3.2 Islanded Scenario 2 (Fig. 5-6, and 100 to 200s in Fig. 5-7)

Active loading of microgrid “A” in scenario 2 had been lowered such that its frequency rose to $f_A = 0p.u..$ Operating points of the microgrids were therefore those marked with “2” in Fig. 5-6(a), whose corresponding active powers requested, and hence actual active powers transferred were all zero. This was observed in Fig. 5-7(b), where both actual powers transferred $P_{A,IC}^*$ and $P_{B,IC}^*$ were noted to gradually drop to zero from 100s onwards. Reactive power loadings in both microgrids were also decreased in scenario 2, causing them to move to operating points “2” in Fig. 5-6(b). Their reactive power generations $Q_{A,IC}^*$ and $Q_{B,IC}^*$ were thus zero, as confirmed by the second plot in Fig. 5-7(d). Since active and reactive powers demanded from the interlinking converters

Fig. 5-6. Operating point trajectories on (a) frequency vs. active power and (b) voltage vs. reactive power characteristics when in islanded mode

were zero, they could be turned off to keep operating costs low rather than operating them continuously.

5.2.3.3 Islanded Scenario 3 (Fig. 5-6, and 200 to 250s in Fig. 5-7)

In scenario 3, the only change introduced was to increase the reactive loading of microgrid "B" until its terminal voltage entered the overloaded range. Reactive power $Q_{B,IC}^* = 0.2 \text{ p.u.}$, read from Fig. 5-7(d), was thus generated by interlinking converter "B"

(a)

(b)

(c)

(d)

(e)

Fig. 5-7. Experimental results showing (a) frequency, (b) active power, (c) voltage, (d) reactive power, and (e) dc-link voltage of interlinking converters when in islanded mode

for microgrid “B” from 200s onwards. Interlinking converter “A”, on the other hand, remained off since no reactive power was requested from it and the actual active power transferred by the two converters remained at zero. Steady-state operating points of the two converters were thus those marked with “3” in Fig. 5-6(a) and (b).

5.2.3.4 Grid-Connected Scenario 4 (Fig. 5-8, and 0 to 180s in Fig. 5-9)

Scenario 4 was tested with microgrid “B” tied to the utility grid, emulated by a *California Instruments*⁵ programmable ac source for the experiment. Its voltage and frequency were therefore fixed at 190.5V and 50Hz, corresponding to $1p.u.$ and $0p.u.$ in the under-loaded ranges. Active and reactive powers requested from interlinking converter “B” were hence zero according to (5-5) and (5-8). Microgrid “A”, on the other hand, was loaded such that its voltage and frequency entered their respective overloaded ranges marked by operating points “4a” in Fig. 5-8(a) and (b). It remained at these operating points from 0 to 20s, during which the interlinking converters were not yet activated. Active and reactive powers generated by the converters from 0 to 20s were thus zero, as seen from Fig. 5-9(b) and (d), respectively. The converters were activated only from 20s onwards, after which interlinking converter “A” started to generate actual active and reactive powers for microgrid “A”. Their values were read as $P_{A,IC}^* \approx -P_{B,IC}^* = 0.25p.u.$ and $Q_{A,IC}^* = 0.2p.u.$ from Fig. 5-9(b) and Fig. 5-9 (d), respectively. With these added capacities provided to microgrid “A”, its source generation could relax slightly, leading to slight increase in its voltage and frequency. Operating points “4a” therefore moved to “4b” in the steady state. Throughout the trajectory, dc-link voltage of the interlinking converters had been kept constant, as seen from Fig. 5-9(e).

⁵ *California Instruments* is the name of the company manufacturing and selling the programmable ac supply.

(a)

(b)

Fig. 5-8. Operating point trajectories on (a) frequency vs. active power and (b) voltage vs. reactive power characteristics when in grid-connected mode

5.2.3.5 Grid-Connected Scenario 5 (Fig. 5-8, and 180 to 250s in Fig. 5-9)

From 180 to 250s, active and reactive power loadings of microgrid “A” were reduced until its frequency and voltage rose to $f_A = 0p.u.$ and $V_A = 1.05p.u.$, indicated by those steady-state operating points marked with “5” in Fig. 5-8(a) and (b). Since they were in the under-loaded ranges, their requested and hence actual active and reactive power flows were zero. These were clearly seen in Fig. 5-9(b) and (d), where $P_{A,IC}^* \approx -P_{B,IC}^*$ and $Q_{A,IC}^*$ gradually dropped to zero.

(a)

(b)

(c)

(d)

(e)

Fig. 5-9. Experimental results showing (a) frequency, (b) active power, (c) voltage, (d) reactive power, and (e) dc-link voltage of interlinking converters when in grid-connected mode

5.3 Conclusions

A distributed droop scheme for managing power flows among two or more interlinked ac microgrids at different nominal frequencies and voltages has been proposed. With the scheme implemented, interlinking converters tied between any two microgrids will autonomously transfer an appropriate amount of active power from the under-loaded to overloaded microgrid for reinforcement. Independent reactive power reinforcement can also be provided by the interlinking converters for supporting microgrid voltages during high reactive power load conditions. These power flow features are achieved with no requirement for fast communication links and at minimized operating losses for the interlinking converters. Anticipated performances of the scheme have already been tested in experiments, which despite being effective, can further be improved, as discussed in the next chapter.

5.4 Acknowledgement

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- [1]. **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, “Power flow control of interlinked hybrid microgrids”, *In Proceedings of the 15th International Power Electronics and Motion Control Conference, Novi Sad*, pp. DS3b.17-1 - DS3b.17-6, Sept. 2012.
- [2]. **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, “Power flow control of intertied ac microgrids”, *IET in Power Electronics*, vol. 6, no7, pp. 1329-1338, Sep. 2013.

Chapter 6

Distributed Droop Schemes for Interlinked AC Microgrids with Adaptive Capacity Tuning

6.1 Introduction

The interlinking droop scheme proposed in Chapter 5 can further be improved by adaptively tuning the generation capacity values at different loading levels. With adaptive tuning, generation responsibilities shared between the DG and interlinking converters can be distinguished such that the DGs focus more on supplying active power, while the interlinking converters try to meet the reactive power demand during heavy loading. A second modification is then introduced by adding power export function to the interlinking active power droop characteristics. This modification causes the under-loaded microgrid to export surplus power to the other microgrid when it is tied to the utility grid. It thus allows the DGs to operate at higher, more efficient generation levels with better voltage and reactive power regulation achieved. Methodology, implementation details and experimental results for the schemes are discussed in subsequent sections.

6.2 Distributed Droop Scheme with Adaptive Capacity Tuning

Considering the example of two interlinked ac microgrids shown in Fig. 6-1, for active power transfer between two microgrids, it is necessary for one microgrid to have surplus power, whereas for reactive power, it doesn't need to be transferred but can locally be produced by interlinking converters "A" and "B" independently. With this basic understanding, the distributed power management scheme is proposed for realizing the interlinking of microgrids that adaptively distribute the generation responsibilities among the DGs and interlinking converters depending on their present loading conditions. The proposed distributed droop scheme allows DGs in the microgrids to concentrate more on active power harnessing and the interlinking converters focus more on meeting the load reactive demand. If necessary, backup active power from an under-loaded microgrid can also be transferred to an overloaded microgrid, allowing it to supply loads in excess of its rated capacity. The adjustment causes energy harnessed from the sources to be maximized, operating time and losses of the converters to be minimized, and reserve sharing to be realized again with no installed backup capacities.

Fig. 6-1. Interlinked microgrids operating at different voltages and/or frequencies.

The proposed scheme in this section is fully autonomous, based on local variables (voltages and frequencies) and independent of fast communication links. The detail methodology of proposed scheme and their performance validation through experiment are discussed in the subsequent sections.

6.2.1 Methodology

The methodology is explained for two interlinked microgrid example shown in Fig. 6-1.

6.2.1.1 DG Converter Control within Individual Microgrids

Before designing the droop scheme for DG converters found in interlinked microgrids, their respective operating features are comprehended by the following points.

- DGs are connected directly to the sources. Where possible, they should hence focus more on transferring active power to the microgrids.
- Usually unidirectional, and hence only need to consider load conditions at the terminals directly connected to the microgrids.

Based on these desired features, the revised droop scheme for DG converter has been developed in the following section.

To avoid fast communication links, DGs in a microgrid can be controlled by the traditional droop method, which operating principles and variants have been discussed in Chapter 2, and will hence not be repeated. Instead, the focus here should more be the formulation of modifications to the basic droop method that can further improve power generation when multiple microgrids are interlinked. To do that, the droop lines shown for microgrid “ x ” (= “ A ” or “ B ”) in Fig. 6-2 are reviewed first, which expressions for DG/source unit “ y ” are re-written as follows.

Fig. 6-2. Active and reactive power droop lines for microgrids and interlinking converters

$$f_{xy}^* = f_{x,max} + m_{xy}P_{xy} \quad (6-1)$$

$$V_{xy}^* = V_{x,max} + n_{xy}Q_{xy} \quad (6-2)$$

In (6-1) and (6-2), superscript “*” and subscript “max” have been added to represent reference and maximum values, respectively. Variables f_{xy}^* and V_{xy}^* are therefore the microgrid reference frequency and voltage determined from their maximum values and measured active and reactive powers.

Also notated in (6-1) and (6-2) there are m_{xy} and n_{xy} , representing the active and reactive power droop coefficients (or gradients of the droop lines), respectively. The droop coefficients are small negative values, which for cases of multiple DGs (including energy storage systems), should be set according to (6-3).

$$m_{x1}S_{x1,max} = m_{x2}S_{x2,max} = m_{x3}S_{x3,max} = \dots$$

$$n_{x1}S_{x1,max} = n_{x2}S_{x2,max} = n_{x3}S_{x3,max} = \dots \quad (6-3)$$

In (6-3), $S_{xy,max}$ represents the source kVA rating. With (6-3) enforced, sources within the microgrid will share the active and reactive power demands proportionally based on their ratings. This works fine in a single microgrid, where the DGs and DG converters are the only generators of active and reactive powers. However, with multiple microgrids interlinked, interlinking converters placed between any two of them can serve as additional generators of active and reactive powers, which operating constraints may not be the same as the DGs.

Modifications to the droop tuning principles to incorporate the different power generator characteristics may therefore result in improved performances. Particularly, for the DGs within each microgrid, their active power generation should be prioritized at high load to draw the maximum amount of energy from the distributed sources. To remain within their converter kVA limits, their reactive power generation must correspondingly be reduced. The reduced reactive power is instead supplied by the interlinking converters to avoid unnecessary load shedding. The interlinking converters can supply active power too, but would usually be less efficient, as compared to reactive power. To illustrate, Fig. 6-2 is referred to, where it is assumed that microgrid “A” demands some active and reactive powers from the interlinking converters. Providing reactive support would require operating interlinking converter “A” only, but to transfer active power without varying the dc-link voltage, both interlinking converters “A” and “B” must be operating. It can hence be more efficient if the intertied system is coordinated such that the DGs concentrate more on active power generation, while the interlinking converters concentrate more on reactive power generation to keep their operating losses low.

With the above approach defined, active power droop coefficients of DGs within microgrid “x” should be tuned according to (6-4) and not (6-3).

Fig. 6-3. Realization of microgrid droop-controlled DG

$$m_{x1}P_{x1,max} = m_{x2}P_{x2,max} = m_{x3}P_{x3,max} = \dots;$$

$$P_{xy,max} = \sqrt{S_{xy,max}^2 - \left(Q_{xy,max}\big|_{P_{xy,max}}\right)^2} \quad (6-4)$$

In (6-4), $Q_{xy,max}$ is a function decreasing with increase in active generation P_{xy} . Notation $Q_{xy,max}\big|_{P_{xy,max}}$ is therefore the maximum reactive power that DG unit “y” can produce when it is at its maximum active power generation of $P_{xy,max}$. Value for $Q_{xy,max}\big|_{P_{xy,max}}$ is user-defined, and should in general be chosen such that critical loads can ride through periods of interlinking converter failure or scheduled maintenance. Shedding of non-critical loads is however necessary if loading is high during these periods of interlinking shutdown.

Complementing (6-4), the reactive droop coefficients should be tuned according to (6-5), where an expression for computing $Q_{xy,max}$ at different P_{xy} is also given. Since

$Q_{xy,max}$ is varying, the droop coefficients or gradients are also varying, as seen from the reactive droop lines drawn on the left and right of Fig. 6-2 for microgrids “A” and “B”.

$$n_{x1}Q_{x1,max}|_{P_{x1}} = n_{x2}Q_{x2,max}|_{P_{x2}} = n_{x3}Q_{x3,max}|_{P_{x3}} = \dots$$

$$Q_{xy,max}|_{P_{xy}} = \sqrt{S_{xy,max}^2 - P_{xy}^2} \leq S_{xy,max} \quad (6-5)$$

6.2.1.2 Control of Interlinking Converters

As drawn in Fig. 6-1, the simplest interlinking converters would consist of two back-to-back six-switch converters, whose qualitatively functionalities are recaped as follows.

- To complement reactive power generation in the microgrid especially under high loading conditions, during which the source reactive power has been reduced according to (6-5).
- To transfer active power from an under-loaded microgrid to an overloaded microgrid. Reserve sharing is thus effected without introducing extra backup generators.
- To properly regulate power flow so that their operating time and hence losses are minimized. This can be done by, for example, generating no extra active and reactive powers when both microgrids are under-loaded, and hence do not require additional support. Interlinking powers should also be zero when both microgrids are heavily overloaded, and hence do not have extra generating capacities for sharing.

Realizing the above functionalities would strictly require the interlinking converters to “know” the consolidated DG generating conditions of each microgrid. Here, consolidated, rather than individual, DG conditions are mentioned because at the terminals of the interlinking converters, individual details within the two microgrids

cannot possibly be seen. Because of that, subscript “y”, representing individual source unit, will be omitted from subsequently derived droop expressions. Returning to the consolidated source or microgrid generating conditions, they can be detected by measuring the microgrid frequencies and voltages, which are linearly related to active and reactive powers according to (6-1) and (6-2). Different thresholds can then be set for the frequencies and voltages to distinguish when the microgrids are under-loaded (UL), overloaded (OL) or heavily overloaded (HOL) in terms of active and reactive powers. Based on the classifications, the interlinking converters can promptly make the appropriate power flow decisions using only variables measured locally. The interlinking droop scheme is hence autonomous, which operating details are presented shortly.

A. Interlinking Reactive Power Droop Characteristics

In Section 6.2.1.1, it is mentioned that reactive power generation in microgrid “x” will be reduced at high active loading conditions. The amount reduced must instead be supplied by interlinking converter “x”, whose kVA rating $S_{x,IC,max}$ must be higher than that after incorporating a comfortable margin to permit some active power transfer at high reactive loading, if desired. On the other hand, when the microgrid reactive loading is low, reactive support from the interlinking converter is not needed since DGs in the microgrid can promptly meet the load reactive requirements. The interlinking converter can hence be turned off to minimize its operating losses.

With these considerations incorporated, two interlinking reactive power droop characteristics are drawn in the middle of Fig. 6-2 to respond to reactive demands from the two microgrids. Their mathematical representations are given in (6-6) given below,

$$Q_{x,IC}^* = \begin{cases} 0, & V_{x,OL} < V_x \leq V_{x,max} \rightarrow \text{Underloaded} \\ n_{x,IC}(V_x - V_{x,OL}), & V_{x,HOL} < V_x \leq V_{x,OL} \rightarrow \text{Overloaded} \\ Q_{x,IC,max}, & V_{x,min} \leq V_x \leq V_{x,HOL} \rightarrow \text{Heavily Overloaded} \end{cases}$$

$$x = A \text{ or } B \text{ (6-6)}$$

In (6-6), $n_{x,IC}$ is the interlinking reactive power droop coefficient and subscripts IC , OL and HOL are used for representing interlinking converter, overloaded threshold and heavily overloaded threshold, respectively. As intended, (6-6) gives rise to zero reactive power command for interlinking converter “ x ” when its detected terminal voltage for microgrid “ x ” lies in the UL range. The interlinking converter can then be turned off if its active power command, discussed in the next subsection, is also zero. Upon the reactive loading in microgrid “ x ” increases, its accompanied terminal voltage detected by interlinking converter “ x ” falls into the OL range. Reactive power support from the interlinking converter then gradually increases along the usual linear droop characteristic until it saturates at a value marked by $Q_{x,IC,max}$ in the HOL range. Limit $Q_{x,IC,max}$ can be set equal to the interlinking converter rating $S_{x,IC,max}$ if active power transfer during heavy reactive power loading is not intended.

The characteristics described above can, in principle, operate independently since reactive powers generated by interlinking converters “ A ” and “ B ” need not be balanced. It is therefore possible to have both interlinking converters turned off, one of them turned on or both of them turned on. The second scenario is however not possible with active power transfer, where power balance must be maintained at both terminals of the interlinking converters. It can therefore be more efficient if the interlinking converters are designed to focus more on reactive power generation.

Fig. 6-4. Realization of interlinking converter droop control scheme

B. Interlinking Active Power Droop Characteristic

One of the reasons for tying microgrids together is to share their active power capacities so that backup generators need not be kept as reserves. For that, a mechanism for controlling the interlinking converters is required, which as per reactive power control, is effected by two interlinking active droop characteristics shown in the middle of Fig. 6-2. Mathematically, they can be represented by (6-7)

$$P'_{x,IC} = \begin{cases} 0, & f_{x,OL} < f_x \leq f_{x,max} \rightarrow \text{Underloaded} \\ m_{x,IC}(f_x - f_{x,OL}), & f_{x,HOL} < f_x \leq f_{x,OL} \rightarrow \text{Overloaded} \\ P_{x,IC,max}, & f_{x,min} \leq f_x \leq f_{x,HOL} \rightarrow \text{Heavily Overloaded} \end{cases} \Rightarrow \begin{cases} P_{A,IC,max} = P_{B,max} \\ P_{B,IC,max} = P_{A,max} \end{cases} \quad (6-7)$$

In (6-7), $m_{x,IC}$ is the interlinking active droop coefficient and $P'_{x,IC}$ is the active power requested by microgrid “x”, which should not be confused with the actual active power transferred by the interlinking converters.

Value for $P'_{x,IC}$ is determined by the detected frequency in microgrid “x”, which when in the UL range, gives rise to zero active power requested by the self-sufficient microgrid “x”. Its value increases only when the detected frequency enters the OL range, before saturating at $P_{x,IC,max}$ in the HOL range. Value for $P_{x,IC,max}$ should be fixed according to (6-7), whose reasoning can be explained with the example of microgrid “A” requesting for $P_{A,IC,max}$ from microgrid “A”. The maximum amount that can be provided by microgrid “B” is no doubt its rated active power value $P_{B,max}$ if its own loading is at zero. Therefore, $P_{A,IC,max}$ should be set equal to $P_{B,max}$ (or lower) with the same reasoning applicable to $P_{B,IC,max}$.

The requested active power $P'_{x,IC}$ should not be immediately supplied by interlinking converter “x” because of the requirement to maintain power balance at the terminals of the two interlinking converters. It is therefore important for the interlinking droop scheme to consider power requests from both microgrids before deciding on the actual active power amount to transfer. One expression that can perform the necessary is given in (6-8), which when implemented, will give rise to the following intended results.

- Actual active powers transferred by the interlinking converters $P_{A,IC}^*$ and $P_{B,IC}^*$ are always equal, but with opposite polarities when in the steady state.
- Their values are zero when both microgrids are UL, and hence do not need additional active supports. Their values are again zero when both microgrids are HOL, and hence do not have extra generation capacities for sharing. The interlinking converters can thus be turned off if their respective reactive power generations are also at zero.

- Their values are non-zero under other conditions. The cap is at microgrid “B” rating $P_{B,max}$ if power is transferred from microgrid “B” to “A”. Similarly, for the reverse flow of power from microgrid “A” to “B”, the power transfer is capped at $P_{A,max}$.

$$P_{A,IC}^* = -P_{B,IC}^* = \begin{cases} \left(\frac{P'_{A,IC}}{P_{A,IC,max}} - \frac{P'_{B,IC}}{P_{B,IC,max}} \right) \times P_{A,IC,max}, & \text{if positive} \\ \left(\frac{P'_{A,IC}}{P_{A,IC,max}} - \frac{P'_{B,IC}}{P_{B,IC,max}} \right) \times P_{B,IC,max}, & \text{if negative} \end{cases} \Rightarrow \begin{cases} -P_{A,max} \leq P_{A,IC}^* \leq P_{B,max} \\ -P_{B,max} \leq P_{B,IC}^* \leq P_{A,max} \end{cases} \quad (6-8)$$

The above-described active power transfer works fine with large enough interlinking converter ratings. It must however be modified slightly if smaller rated interlinking converters are preferred. The recommended modification is shown in (6-9),

$$P_{A,IC}^{**} = -P_{B,IC}^{**} = \begin{cases} \text{sign}(P_{A,IC}^*) \times \min \left(\sqrt{S_{A,IC}^2 - (Q_{A,IC}^*)^2}, \sqrt{S_{B,IC}^2 - (Q_{B,IC}^*)^2} \right), & \text{if smaller than } |P_{A,IC}^*| \text{ in magnitude} \\ P_{A,IC}^*, & \text{otherwise} \end{cases} \quad (6-9)$$

In (6-9), the original active power transfer $P_{x,IC}^*$ has been compared with the remaining interlinking converter capacities after accounting for their reactive power generations. If $P_{x,IC}^*$ is larger, a modified actual power reference $P_{x,IC}^{**}$, capped at the lowest remaining capacity, will be used instead to avoid stressing the converters improperly.

6.2.2 Experimental Setup

To verify the integrated performances of the microgrid and interlinking droop schemes proposed in this section, the experimental setup shown in Chapter 5, Fig. 5-4 was used. Two converters were for emulating microgrids “A” and “B”, while the other two were for forming the back-to-back interlinking converters (also shown in Fig. 6-3 and Fig. 6-4). The converters were digitally controlled through dSPACE 1103 and dSPACE

1104 with their respective active power, reactive power, frequency and voltage ranges listed in TABLE 6-1. These ranges were chosen to satisfy the usual tradeoff between regulation and sharing accuracy of any droop controller with no other consideration needed.

Block diagram showing realization of the above interlinking droop control can be found in Fig. 6-4, which comparatively is different from the individual microgrid source control shown in Fig. 6-3. The former measures voltage magnitude and frequency, usually through a phase-locked-loop (PLL), before generating the required active and reactive power references for the interlinking converters. The latter does the reverse of measuring voltages and currents for computing active and reactive powers, before using them to generate the required voltage and frequency references for the DGs. Their implementations and theoretical backgrounds are therefore different even though they are based on the same droop principles of active power versus frequency and reactive power versus voltage magnitude.

Besides the above observations, it can be seen in Fig. 6-4 that an additional activation trigger has been introduced. The thought is to activate the interlinking converter operation only when its active and reactive power generations rise above some specified thresholds $P_{x,act}$ and $Q_{x,act}$, which can be fractional multiples of the converter rating (e.g. 25% of $S_{x,IC,max}$). This can, in principle, further minimize losses since it is usually not efficient to operate converter at such low power value.

TABLE 6-1: Experimental droop parameters and ratings

Microgrid “A”	
kVA Rating $S_{A,max}$	1 kVA
Maximum $P_{A,max}$	0.96 kW
Maximum $Q_{A,max}$ Range	$0.28 \text{ kVAr} \leq Q_{A,max} \leq 1 \text{ kVAr}$
Frequency f_A Range	$59 \text{ Hz} \leq f_A \leq 61 \text{ Hz}$
Voltage V_A Range	$171.4 \text{ V} \leq V_A \leq 209.5 \text{ V}$
Interlinking Converter “A”	
kVA Rating $S_{A,IC,max}$	1 kVA
Maximum $P_{A,IC,max}$	1 kW
Maximum $Q_{A,IC,max}$	1 kVAr
Activation Threshold $P_{A,act}$	0.25 kW
Activation Threshold $Q_{A,act}$	0.25 kVAr
Frequency f_A UL Range	$60 \text{ Hz} < f_A \leq 61 \text{ Hz (UL)}$
Frequency f_A OL Range	$59.2 \text{ Hz} < f_A \leq 60 \text{ Hz (OL)}$
Frequency f_A HOL Range	$59 \text{ Hz} \leq f_A \leq 59.2 \text{ Hz (HOL)}$
Voltage V_B UL Range	$186.7 \text{ V} < V_A \leq 209.5 \text{ V (UL)}$
Voltage V_B OL Range	$171.4 \text{ V} < V_A \leq 186.7 \text{ V (OL)}$
Voltage V_B HOL Range	No HOL range
Interlinking Converter “B”	
kVA Rating $S_{B,IC,max}$	1 kVA
Maximum $P_{B,IC,max}$	1 kW
Maximum $Q_{B,IC,max}$	1 kVAr
Activation Threshold $P_{B,act}$	0.25 kW
Activation Threshold $Q_{B,act}$	0.25 kVAr
Frequency f_B UL Range	$50 \text{ Hz} < f_B \leq 51 \text{ Hz(UL)}$
Frequency f_B OL Range	$49.2 \text{ Hz} < f_B \leq 50 \text{ Hz(OL)}$
Frequency f_B HOL Range	$49 \text{ Hz} \leq f_B \leq 49.2 \text{ Hz(HOL)}$
Voltage V_B UL Range	$186.7 \text{ V} < V_B \leq 209.5 \text{ V (UL)}$
Voltage V_B OL Range	$171.4 \text{ V} < V_B \leq 186.7 \text{ V (OL)}$
Voltage V_B HOL Range	No HOL range
Microgrid “B”	
kVA Rating $S_{B,max}$	1 kVA
Maximum $P_{B,max}$	0.96 kW
Maximum $Q_{B,max}$ Range	$0.28 \text{ kVAr} \leq Q_{B,max} \leq 1 \text{ kVAr}$
Frequency f_B Range	$49 \text{ Hz} \leq f_B \leq 51 \text{ Hz}$
Voltage V_B Range	$171.4 \text{ V} \leq V_B \leq 209.5 \text{ V}$

TABLE 6-2: Voltages and frequencies detected by interlinking converters under different operating conditions

Entity	Measured Parameter	Case 1	Case 2	Case 3
Interlinking Converter “A”	Voltage V_A	181.0 V → Reactive OL	190.5 V → Reactive UL	190.5 V → Reactive UL
	Frequency f_A	59.8 Hz → Active OL	59.4 Hz → Active OL	59.4 Hz → Active OL
Interlinking Converter “B”	Voltage V_B	181.0 V → Reactive OL	175.3 V → Reactive OL	194.3 V → Reactive UL
	Frequency f_B	50 Hz → Active UL	49.1 Hz → Active HOL	49.4 Hz → Active OL

TABLE 6-3: Actual active and reactive power generated under different operating conditions

		Case 1	Case 2	Case 3
	Microgrid “A” Loading	Reactive OL, Active OL	Reactive UL, Active OL	Reactive UL, Active OL
	Microgrid “B” Loading	Reactive OL, Active UL	Reactive OL, Active HOL	Reactive UL, Active OL
Microgrid “A”	Actual P_A	0.6 kW	0.77 kW	0.77 kW
	Actual Q_A	0.62 kVAr	0.3 kVAr	0.3 kVAr
Interlinking Converter “A”	Actual $P_{A,IC}$	0.27 kW	0 kW	0 kW
	Actual $Q_{A,IC}$	0.37 kVAr	0 kVAr	0 kVAr
Interlinking Converter “B”	Actual $P_{B,IC}$	−0.27 kW	0 kW	0 kW
	Actual $Q_{B,IC}$	0.37 kVAr	0.75 kVAr	0 kVAr
Microgrid “B”	Actual P_B	0.5 kW	0.94 kW	0.77 kW
	Actual Q_B	0.62 kVAr	0.32 kVAr	0.34 kVAr

Fig. 6-5. Experimental result for actual active and reactive power generations

6.2.3 Experimental Results and Analysis

The experiment was performed with loading conditions in the two microgrids adjusted to give three different cases/scenarios consecutively. Just to clarify, the loading conditions used during the experiment for this scheme are different than the loading scenarios used in Chapter 5. Voltages and frequencies measured by the interlinking converters for these three cases were summarized in

TABLE 6-2, whose corresponding loading classifications were also indicated (UL, OL or HOL). Based on these classifications, different decisions on power generation were effected for the three cases, whose details are discussed as follows.

6.2.3.1 Case 1

Microgrid “A”, classified as OL for both active and reactive generations, had requested for active and reactive supports from interlinking converter “A”. Microgrid “B”, on the other hand, had requested for reactive power only from interlinking converter “B” to reinforce its OL reactive generation. Being independent, the requested reactive powers were generated by the interlinking converters immediately, whose values were read from either the “0 to 60s” interval of Fig. 6-5 or third column of TABLE 6-3. This was however not the case for the requested active powers, whose values must jointly be substituted into (6-8) and (6-9) to get the actual active powers generated by the interlinking converters. Read from the “0 to 60s” interval of Fig. 6-5 or third column of TABLE 6-3, their values were $P_{A,IC} = 0.27$ kW and $P_{B,IC} = -0.27$ kW, representing a transfer of active power from the UL microgrid “B” to OL microgrid “A”. Being of equal magnitude also guaranteed power balance with no variation of dc-link capacitor voltage observed.

6.2.3.2 Case 2

The loading conditions were changed to case 2, whose reactive classifications caused interlinking converter “A” to generate no reactive power and interlinking converter “B” to generate 0.75 kVAr. Its active power classifications also led to two requested active powers, whose values were close. They gave rise to actual active power values, whose magnitudes were smaller than the activation thresholds (see TABLE 6-1), hence causing the interlinking converters to turn off if they were also not producing reactive powers. From the values read from the “60 to 160s” interval of Fig. 6-5 or fourth column of TABLE 6-3, interlinking converter “A” with no active and reactive power generation was in fact turned off to minimize losses during the experiment. The same could not be effected on interlinking converter “B”, whose reactive generation was non-zero.

During case 2, load demand in microgrid B is more than its DG rated capacity ($S_{B,max} = 1kVA$), whereas the load demand is $S_L = \sqrt{0.94^2 + 1.07^2} = 1.42kVA$ (~42% higher). This case demonstrates the capacity enhancement of interlinked microgrid with the proposed adaptive capacity tuning, where the reactive power responsibility is automatically transferred to interlinking converters during heavy over loading.

Fig. 6-6. Experimental maximum active and reactive power generation capacities adjustments

TABLE 6-4: Adjustment of maximum active and reactive power values under different operating conditions

		Case 1	Case 2	Case 3
	Microgrid “A” Loading	Reactive OL, Active OL	Reactive UL, Active OL	Reactive UL, Active OL
	Microgrid “B” Loading	Reactive OL, Active UL	Reactive OL, Active HOL	Reactive UL, Active OL
Microgrid “A”	Actual P_A	0.6 kW	0.77 kW	0.77 kW
	Maximum $Q_{A,max}$	0.8 kVAr	0.64 kVAr	0.64 kVAr
Interlinking Converter “A”	Maximum $P_{A,IC,max}$	0.92 kW	1 kW	1 kW
	Actual $Q_{A,IC}$	0.37 kVAr	0 kVAr	0 kVAr
Interlinking Converter “B”	Maximum $P_{B,IC,max}$	0.92 kW	0.66 kW	1 kW
	Actual $Q_{B,IC}$	0.37 kVAr	0.75 kVAr	0 kVAr
Microgrid “B”	Actual P_B	0.5 kW	0.94 kW	0.77 kW
	Maximum $Q_{B,max}$	0.86 kVAr	~0.36 kVAr	0.64 kVAr

6.2.3.3 Case 3

The loading conditions were finally changed to case 3, where both microgrids were UL in terms of reactive power generation, but OL in terms of active power generation. Reactive powers generated by the interlinking converters were therefore zero. Their requested active powers were however non-zero but equal, which when substituted into (6-8) and (6-9), gave rise to zero actual active powers transferred by the interlinking converters. These values could be read from the “160 to 200s” interval of Fig. 6-5 or last column of TABLE 6-4. Since the active and reactive power generations here were all zero, both interlinking converters were turned off to minimize losses, as intended.

6.2.3.4 Adaptively Adjusted Power Limits

As explained in Section 6.2.1.1, maximum reactive power $Q_{x,max}$ that could be produced by each microgrid was constantly changing with its active power generation P_x (see (6-5)). To illustrate the variation, values for $Q_{x,max}$ and P_x were plotted on the left and right of Fig. 6-6 for the two microgrids. Their values were also tabulated in the third and last rows of TABLE 6-4 for easier reference. Besides this variation, variation experienced by the interlinking converter when computing its remaining capacity using (6-9) could also be plotted. The variation was shown in the middle of Fig. 6-6, which for convenience of notating, was labeled as $P_{x,rem} = \sqrt{S_{x,IC}^2 - (Q_{x,IC}^*)^2}$. Relevant values read from the plots were also tabulated in the fourth and fifth rows of TABLE 6-4.

Summary and moving forward...

In above sections, the distributed droop scheme with adaptive capacity tuning has been investigated thoroughly. The theoretical findings have been validated through experiment, as summarized in the following points:

- The proposed adaptive tuning concept can help to release stress on microgrid DGs by prioritizing reactive power supply from interlinking converters under heavy loading conditions. This feature can be realized from the case 2 results given in Subsection 6.2.3.2.
- The supply capacity of the interlinked microgrid can be enhanced, as demonstrated during the case 2 in Subsection 6.2.3.2, where microgrid B is 42% overloaded.
- At the same time, scheme allows active power reserve sharing among interlinked microgrids, when either one the interlinked microgrid has surplus power or other

microgrid is heavy-loaded, as shown from the experimental result for case 1 explained in Subsection 6.2.3.1.

- The scheme minimizes interlinking converter losses by turning it off as and when possible. This feature has been demonstrated from the experimental result for case 3 given in Subsection 6.2.3.3.

In the subsequent section of this Chapter, the proposed adaptive capacity tuning droop scheme for interlinked microgrids is further modified to include the power export function, based on which under-loaded microgrid can export surplus power to over-loaded or grid connected microgrid and hence avoid DGs operation at inefficient loading region. Apart from the power export feature, alternative scheme for reactive power control in interlinking converter and DGs has been introduced.

6.3 Modified Droop Scheme with Adaptive Capacity Tuning and Power Export

6.3.1 Overview

This is an alternate approach for power flow management among interlinked microgrids where some new features and variations have been introduced to the aforementioned droop scheme for interlinked microgrid. These feature and variations are summarized below.

- Active power export feature has been included in interlinking converters droop characteristics. Power export feature can be realized when one of the interlinked microgrid is under-loaded, the interlinking converters can then export power from under-loaded to the heavy-loaded standalone or grid-connected microgrid.
- Reactive power droop characteristics are modified for better voltage and reactive power regulation.
- The proposed scheme performance has been validated when one of the interlinked microgrid is connected to the utility grid.

6.3.2 Methodology

6.3.2.1 Interlinked Droop Scheme – Islanded Mode

For the example system shown in Fig. 6-1, islanded mode, regardless of intended or unintended, is initiated by turning off the breaker or static switch placed between microgrid “A” and the utility grid. When in this mode, power flows through the converters can be realized by the following autonomous scheme designed with the converter distinctive features taken into consideration.

A. DGs Active Power Generation

Note: Microgrid DGs active power control is similar to DG control given in Subsection 6.2.1.1, however, repeated in the following section to understand the overall implementation of modified scheme.

Priority of the DG converters has since been identified as active power generation (refer to Subsection 6.2.1.1). Their individual maximum active power limits $P_{x,max}$ can hence be written by (6-10).

$$P_{xy,max} = S_{xy}; x=A \text{ or } B \text{ and } y=\text{DG number in microgrid} \quad (6-10)$$

Fig. 6-7. Control strategies for interlinked microgrids (a) active power and (b) reactive power droop lines for DG and interlinking converters tied to microgrid "A"

This maximum active power should be produced when the microgrid frequency drops from its maximum to minimum permitted values notated as $f_{x,max}$ and $f_{x,min}$, respectively. Its corresponding droop equation can hence be expressed as (6-11), whose graphical illustration for microgrid A can be found at the top left of Fig. 6-7(a).

$$f_{xy}^* = m_{xy}P_{xy} + f_{x,max}, \quad m_{xy} = \frac{f_{x,min} - f_{x,max}}{P_{xy,max}} < 0 \quad (6-11)$$

In (6-11), m_{xy} is the active power droop coefficient of the DG converters, whose value is usually small and negative. Also included in (6-11) is superscript * for representing the commanded reference value, which for a DG converter, is its frequency value.

Equation (6-11) is no doubt similar to the traditional droop scheme, where the DG voltages and currents are measured for computing P_{xy} , before using it to determine f_{xy}^* for tracking by using control block diagram showing this regulator can be found in Fig. 6-8.

B. DGs Reactive Power Generation

The same reactive power droop principles can be applied to the DG converters after introducing a slight modification to account for their prioritized focus on active power generation. The required modification is shown in (6-12), where their maximum permitted reactive generation $Q_{xy,max}$ is constantly varied with their present active power P_{xy} generated.

$$Q_{xy,max} = \sqrt{S_{xy}^2 - P_{xy}^2} \quad (6-12)$$

The effect introduced by (6-12) is a variable reactive droop coefficient, whose expression and associated droop line are listed as follows.

$$V_{xy}^* = \begin{cases} PI_3 \times (0 - Q_{xy}), & V_{x,int} \leq V_x \leq V_{x,max} \\ n_{xy} Q_{xy} + V_{x,int}, & V_{x,min} \leq V_x < V_{x,int} \end{cases}, \quad n_{xy} = \frac{V_{x,min} - V_{x,int}}{Q_{xy,max}} < 0 \quad (6-13)$$

where $V_{x,int}$ is an intermediate voltage level defined to create two sub-ranges shown in Fig. 6-7(b). The lower sub-range is the usual droop line, while the upper sub-range is a region created with zero reactive generation. The latter is optional though, since it merely allows the DG converters to concentrate fully on active power generation during low load demand. The full reactive load is hence met by the interlinking converters, which can surely fulfill their prioritized duty during low load conditions.

C. Interlinking Converters Active Power Generation

The droop scheme for interlinking converters described in Subsection 6.2.1.2(B) is however not suitable for the droop scheme proposed in this section, where power export options has been included, as shown in Fig. 6-7(a). The control detail for the modified droop scheme is explained below.

The interlinking converters sense the conditions in both microgrids before deciding on a single active power value to transfer from one microgrid to the other. Ignoring losses, dc-link voltages of the interlinking converters will then be held constant, which in practice, can still be guaranteed by a slight modification which will be discussed later. It is thus important for the interlinking converters to determine their single active power transfer reference. This can be done by first measuring frequency f_x in microgrid x using the phase-locked-loop (PLL) shown in Fig. 6-8. The measured f_x can then be processed by (6-14) to (6-16).

$$P'_{x,IC} = \begin{cases} S_{x,IC}(f_x - f_{x,L})/(f_{x,min} - f_{x,L}), & f_{x,min} \leq f_x < f_{x,L} \rightarrow \text{Overloaded (OL)} \\ 0, & f_{x,L} \leq f_x < f_{x,U} \rightarrow \text{Zero Transfer (ZT)} \\ -S_{x,IC}(f_x - f_{x,U})/(f_{x,max} - f_{x,U}), & f_{x,U} \leq f_x < f_{x,max} \rightarrow \text{Underloaded (UL)} \end{cases} \quad x=A \text{ or } B \quad (6-14)$$

$$P_{IC}^* = (P'_{A,IC} - P'_{B,IC}) \times P_{IC,max}/S_{x,IC} \quad (6-15)$$

$$P_{IC,max} = \min \left(P_{x,IC,max} = \sqrt{S_{x,IC}^2 - Q_{x,IC}^2}, \text{ where } x = A \text{ or } B \right) \quad (6-16)$$

Fig. 6-8. Control block diagram for interlinked microgrids

By applying (6-14) or its illustration shown at the top right of Fig. 6-7(a), the frequency range occupied by f_x is effectively divided into three sub-ranges named as under-loaded (UL), zero transfer (ZT) and overloaded (OL). In the UL sub-range, frequency f_x is comparatively high, meaning that load demand and source generation in microgrid x are

low. The DGs hence have extra capacity for generating active power for exporting out of microgrid x ($P'_{IC,x} < 0$). At the other extreme in the OL range, the load and DG capacity in microgrid x are close to their rated values, and would hence request for active power import to microgrid x ($P'_{x,IC} > 0$). There can also be a third ZT sub-range, during which no active power transfer is demanded by microgrid x . Ideally, the ZT sub-range should be placed over the nominal frequency of the microgrid x so that operating losses of the interlinking converters can be kept low if the other microgrid is also in its nominal ZT sub-range. The ZT sub-range will in no way affect the flexibility of reserve sharing between the microgrids when needed.

Equation (6-14) alone is however insufficient since it gives rise to two distinct values $P'_{A,IC}$ and $P'_{B,IC}$, which must be merged on a single power transfer value P_{IC}^* . This can be done by (6-15) based on the power flow directions drawn in Fig. 6-8. In addition, (6-15) helps to scale P_{IC}^* to below its permitted value $P_{IC,max}$, which can be found by (6-16). Equation (6-16) mainly enforces a criterion mentioned in Subsection 6.2.1.2, where it is reasoned that the interlinking converters should concentrate more on reactive power generation. Their active power capacity is hence given by (6-16) after taking the converter rating S_{IC} and the present reactive generation $Q_{x,IC}$ for both microgrids into consideration. The final determined power reference P_{IC}^* is then subtracted by its corresponding measured value before fed into the PI_1 controller shown in Fig. 6-8. Output from PI_1 is a reference frequency value f_x^* to be tracked by the standard double-loop regulator. Besides PI_1 , an additional PI_2 controller can be seen, whose input is the dc-link voltage error and output is a small active power value ΔP_{IC}^* . This value can be added to P_{IC}^* to account for losses in the converters.

D. Interlinking Converter Reactive Power Generation

Unlike active power, reactive power generation is prioritized to the interlinking converters, whose maximum reactive generation $Q_{x,IC,max}$ should hence be set as:

$$Q_{x,IC,max} = S_{IC} \quad (6-17)$$

Also, the reactive power control for interlinking converter is different than the proposed in the previous Subsection 6.2.1.2(A). Corresponding equation for the proposed reactive power droop curves shown in Fig. 6-7(b) can be written as (6-18),

$$V_{x,IC}^* = n_{x,IC} Q_{x,IC} + V_{x,max}, \quad n_{x,IC} = \frac{V_{x,min} - V_{x,max}}{Q_{x,IC,max}} < 0 \quad (6-18)$$

In (6-18), $n_{x,IC}$ is the small negative reactive power droop coefficient of the interlinking converters. Being similar to the traditional droop scheme, its realization in Fig. 6-8 is also similar with its reactive power $Q_{x,IC}$ computed first from its measured terminal voltages and currents. The computed value is then fed to (6-18) to obtain voltage reference V_x^* for tracking by the dual-loop regulator, as shown in Fig. 6-8.

To recap, in the control scheme proposed in Subsection 6.2.1.2(A), the reactive power reference $Q_{x,IC}^*$ is calculated based on interlinking converter terminal voltage and tracked using *PI* controller. Also to be noted, the voltage reference in the previous proposed scheme is provided by the DGs, whose reactive power maximum capacity and droop coefficient are changing at every instant due to proposed tuning by (6-12), that may not be the preferred solution from voltage regulation point of view, especially under the load varying condition. An alternative scheme is thus proposed in this section, where the DGs voltage reference V_x^* is calculated using (6-18) and tracked through dual loop controller. With the proposed reactive power scheme, the interlinking converters will regulate the microgrid voltage while at the same time will supply the desired

reactive power to the interlinked microgrids. The main advantage of assigning voltage regulation to interlinking converters is its constant droop co-efficient since the maximum reactive power of the interlinking converters is fixed equal to kVA capacity $\sim Q_{x,IC,max} = S_{x,IC}$, as in (6-17).

6.3.2.2 Interlinked Droop Scheme – Grid-Connected Mode

When in the grid-connected mode, microgrid “A” in Fig. 6-1 is tied to the utility grid. Its frequency and voltage are hence fixed by the utility to their nominal values in the ZT sub-range. If the same interlinked droop scheme is applied, $P'_{A,IC}$ and $Q^*_{A,IC}$ of microgrid A would hence be zero, while $P'_{B,IC}$ and $Q^*_{B,IC}$ of microgrid “B” would continue to vary depending on its loading. From (6-15), the single active power command tracked by the interlinking converters is hence given by (6-19), whose value is:

$$P_{IC}^* = -P'_{B,IC} \times P_{IC,max}/S_{IC} \quad (6-19)$$

- Positive when microgrid “B” is in its UL sub-range ready to export some of its active power to microgrid “A” and the utility grid.
- Zero when microgrid “B” is in its nominal ZT sub-range.
- Negative when microgrid “B” is in its OL sub-range ready to import some active power from microgrid “A” and the utility grid.

These are the same intended operating features as before for active power transfer. Reactive power transfer also remains unchanged because of its independence between the two microgrids. The proposed scheme is hence anticipated to work fine in both grid-connected and islanded modes. With this understanding now established, advantages of the interlinked droop scheme can broadly be summarized as:

- Fully autonomous control of the interlinking and DG converters without demanding for fast communication links.
- Higher active power generation by the DG converters since reactive power generation has been prioritized to the interlinking converters.
- Higher efficiency since active power would automatically be transferred from the under-loaded to overloaded microgrid. Utilization of the DGs would hence be even more, avoiding the usually low efficiency at extreme low active power generation (e.g. 20% of rated value).
- Narrower frequency variation contributed by the more even DGs utilization explained above.

6.3.3 Experimental Setup

The experimental set up shown in Chapter 5, Fig. 5-4 is used for testing the proposed interlinked microgrid scheme. The DGs converters and interlinking converters similar to the power stage representation are also shown at the top of Fig. 6-8. Their specifications and ratings are given in TABLE 6-5 together with parameters used with the interlinked droop scheme. Results obtained are presented in per-unit (*p.u.*), which for power and voltage, are simply their actual values divided by their chosen base values included in TABLE 6-5.

Conversion for frequency is however done similar to the normalization proposed in the Chapter 5, rewritten by (6-20), which effectively places the frequencies of the two microgrids in the same common range from -1 to 1 . This better illustrates their relative variations without modifying the interlinked droop concepts proposed in the section.

$$f_x(p.u.) = \frac{f_x - Mean}{0.5 \times Range} = \frac{2f_x - (f_{x,max} + f_{x,min})}{f_{x,max} - f_{x,min}} \quad (6-20)$$

TABLE 6-5: Ratings and parameters used for experimental testing

Microgrid A	kVA Rating $S_{DG,A}$	2 kVA
	Frequency f_A Range	$59 \text{ Hz} \leq f_A \leq 61 \text{ Hz}$
	Voltage V_A Range	$181 \text{ V} \leq V_A \leq 200 \text{ V}$
	Threshold $V_{A,int}$	190.5 V
Microgrid B	kVA Rating $S_{DG,B}$	2 kVA
	Frequency f_B Range	$49 \text{ Hz} \leq f_B \leq 51 \text{ Hz}$
	Voltage V_B Range	$181 \text{ V} \leq V_B \leq 200 \text{ V}$
	Threshold $V_{B,int}$	190.5 V
Interlinking Converter	kVA Rating	2 kVA
	Per Converter S_{IC}	
	Frequency and Voltage Ranges	Same as above
	Thresholds $f_{A,L}, f_{A,U}$	60 Hz, 60.25 Hz
	$f_{B,L}, f_{B,U}$	50 Hz, 50.25 Hz
	Normalization S_{base}, V_{base}	2 kVA, 190.5 V

6.3.4 Experimental Results and Analysis

6.3.4.1 Islanded Mode

The experiment starts with the loads in the two microgrids adjusted to absorb the same active and reactive powers from $t = 0$ to 100 s. Their combined apparent power per

microgrid is computed as $S_{x,load} = 1.22 \text{ p.u.}$ ($x = A$ or B), which is 22% higher than the DG rating of 1 p.u. in each microgrid. Despite that, the interlinked system will still function well because its combined DG and interlinking converter rating per microgrid is given by $\sqrt{1 + 1} = 1.41 \text{ p.u.}$. This value is obtained by assuming that the DG generates full active power only and interlinking converter generates full reactive power only in the extreme case. With the loads adjusted as such, the interlinking converter will transfer no active power according to (6-14) and (6-15). Instead, it generates reactive powers to help meet the load demands in the two microgrids. These power flow expectations have obviously been verified by the waveforms shown in Fig. 6-9(a) and (b) for the interlinking converter. Also shown in Fig. 6-9(c) and (d) is the DG power generation in each microgrid, which as intended, has concentrated more on active power generation, leaving reactive power generation to the interlinking converter.

The active power loads in microgrid “A” and “B” are next reduced to 0.22 p.u. and increased to 1.14 p.u. , respectively, with their reactive powers kept roughly unchanged at 0.79 p.u. from $t = 100 \text{ s}$ onwards. The former is thus under-loaded and hence inefficient, while the latter becomes more overloaded. As directed by (6-14) to (6-16), a net transfer of active power of 0.36 p.u. from the under-loaded to overloaded microgrid then happens, causing the DG active and reactive powers generated in both microgrids to be close even though their loads are sizably different. These findings can clearly be seen in Fig. 6-9 from $t = 100 \text{ s}$ and onwards.

(a)

(b)

(c)

(d)

Fig. 6-9. Experimental results showing (a) active and (b) reactive power flow in interlinking converters, (c) DG converter active and reactive power in microgrid “A” and (d) DG converter active and reactive power in microgrid “B” when operated in islanded mode

Other waveforms that might be of interest are shown in Fig. 6-10 and Fig. 6-12 whose explanations are provided as follows.

- As mentioned in Subsection 6.3.2.1(C), active power capacities $P_{x,IC,max}$ ($x = A$ or B) of the interlinking converter are tuned according to its present reactive power outputs $Q_{x,IC}$. Variations of $P_{x,IC,max}$ as $Q_{x,IC}$ changed for the two load cases are shown Fig. 6-10(a) and (b).
- In contrast to the interlinking converter, Subsection 6.3.2.1(B) explains that the reactive power capacities $Q_{xy,max}$ of the DGs should vary with their actual active power outputs P_{xy} . Variations of $Q_{xy,max}$ in response to P_{xy} are shown Fig. 6-10(c) and (d).
- Voltages and frequencies measured in the two microgrids are shown in Fig. 6-10 (a) and (b). For the latter, the frequencies read after the load change are -0.31 $p.u.$ for microgrid “A” and -0.63 $p.u.$ for microgrid “B”. They correspond to an active power load of 0.22 $p.u.$ in microgrid “A” and a value of 1.14 $p.u.$ in microgrid “B”, together with an interlinking active power transfer of 0.36 $p.u.$ If the transfer has been stopped, the microgrid frequencies would change to -1 $p.u.$ (exceeded and hence capped at the lower limit of -1) and 0.2 $p.u.$, respectively, which are certainly wider apart. The introduced power transfer therefore has the ability of regulating the microgrid frequencies closer, in addition to its smooth reserve sharing among the microgrids without any demand for standby generators.

(a)

(b)

(c)

(d)

Fig. 6-10. Experimental results showing (a) active power tuning of interlinking converter “A” and (b) active power tuning of interlinking converter “B”, (c) reactive power tuning of DG converter in microgrid “A” and (d) reactive power tuning of DG converter in microgrid “B” when in islanded mode

Fig. 6-11. Experimental result showing microgrid (a) voltages and (b) frequencies when in islanded mode

6.3.4.2 Grid-Connected Mode

Microgrid “A” is now connected to the utility grid emulated by a programmable ac source. Its voltage and frequency are hence fixed at the nominal values of 1 $p.u.$ and 0 $p.u.$, respectively. As explained in Subsection 6.3.2.2, the active power exported from microgrid “B” is hence given by (6-19) to be tested with two grid-connected cases. For the first case from $t = 0$ to 100 s in Fig. 6-12 frequency of microgrid “B” is sensed to be in the inefficient under-loaded range. To raise its DG generation, 0.18 $p.u.$ of active power is hence exported out of it. The situation changes from $t = 100$ s onwards, during which frequency of microgrid “B” has lowered to the overloaded range, and hence needs additional generation support. In response, 0.22 $p.u.$ of active power is imported from grid by the interlinking converter.

(a)

(b)

Fig. 6-12. Experimental results showing (a) active powers through interlinking converter and (b) microgrid frequencies when in grid-connected mode

It shall however be noted that the same droop scheme used for islanded interlinked microgrids has been used for grid connected operation without any modification or scheme switching in controller.

6.4 Conclusions

This chapter presents two distributed power management schemes for interlinked microgrids based on the droop operating principles. The concept of adaptive capacity tuning has been proposed, where during heavy load conditions, sources within the interlinked microgrids can concentrate more on harnessing active power, leaving most of the reactive generation to the interlinking converters. Where necessary, the

interlinking converters can also transfer active power from the under-loaded to overloaded microgrid, hence reducing the reserve requirements of the latter.

Besides this, the schemes have other advantages, whose details are summarized, as follows.

- Capacities of the interlinked microgrids can be raised (up to $\sim 40\%$ for the interlinked microgrids considered in this chapter) by shifting reactive power load demand to the interlinking converters during heavy load conditions. The amount of backup reserve can hence be reduced accordingly.
 - In Subsection 6.2.3.2, during case 2, interlinked microgrid B enhanced generation capacity up to 42% is demonstrated.
 - In Subsection 6.3.4.1, during load interval 1(0-100 s), interlinked microgrids enhanced generation capacity up to 22% is demonstrated.
- Frequency regulation in each microgrid is improved as a result of power sharing among the microgrids, rather than operating at extreme values when not interlinked, as demonstrated during the second loading interval result shown in Subsection 6.3.4.1, Fig. 6-9.
- Power transfer ceases when both microgrids do not need additional generation or do not have extra generating capacities for sharing. The interlinking converters can then be turned off to reduce their operating losses. This feature has been demonstrated in the earlier section of this Chapter, Subsection 6.2.3.3, Case 3.
- With power export feature included, exporting of active power from the under-loaded microgrid has the advantage of keeping the microgrid frequencies close to their nominal values, hence raising the DG efficiencies. This feature has been demonstrated through result shown in Subsection 6.3.4.2.

- The proposed power management schemes work effectively with no modification needed even when one or more of the interlinked microgrids are connected to the utility grid, as demonstrated in Subsection 6.3.4.2, Fig. 6-12.

These features are achieved autonomously based only on locally measured variables. Their practicality has already been demonstrated through experimental testing under different load conditions.

6.5 Acknowledgement

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- [1]. **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Distributed control of hybrid AC microgrids with dynamic active and reactive power capacity tuning," *IEEE Energy Conversion Congress and Exposition (ECCE)*, Raleigh, NC, pp.1954-1959, Sept. 2012.
- [2]. **I. U. Nutkani**, P. C. Loh, F. Blaabjerg, "Distributed operation of interlinked AC microgrids with dynamic active and reactive power tuning," *IEEE Trans. of Indus. App.*, vol.49, no.5, pp.2188-2196, 2013.

Chapter 7

Summary and Recommendations for Future Research

7.1 Summary and Conclusions

Distributed droop schemes for standalone and interlinked ac microgrids have been developed and validated through experiments. Particularly, for the standalone autonomous microgrids, concepts related to the characteristic or cost-based droop schemes have been presented, whose operations do not require centralized management through a communication network. When implemented, the schemes produce a reduction in generation cost or a combination of factors grouped together as a weighted cost-function for the considered microgrid. Despite their improved performances, the schemes still retain their simplicity and flexibility like found in the basic droop scheme. Moreover, the schemes have been developed from generic droop principles, which thus allow them to be applied to different types of standalone microgrids.

The droop concepts have next been extended from standalone to interlinked microgrids, where between any two of them is an interlinking power converter. For controlling this power converter, a few power flow management schemes have been developed for ensuring proper active power sharing and reactive power support within the interlinked microgrids. The outcome is an improved performance with lower reserve requirements demanded from the individual microgrids. With the proposed adaptive capacity tuning

technique implemented, combined generation capacity of the interlinked microgrids can also be raised, mainly contributed by the extra reactive power generation provided by the interlinking converters, especially during heavy load conditions. These findings are applicable to tying any number of microgrids with any voltage and frequency values, since they are obtained from generic derivation with the same simplicity of the basic droop scheme retained.

The schemes proposed for standalone and interlinked microgrids are therefore demonstrated to have their own unique advantages tested in experiments. These advantages, when merged, can surely make a significant impact to the future progression of microgrids or smart grids in general. Their continuous development is therefore important with the following few recommended topics probably forming a sound basis to begin with.

7.2 Recommendations for Future Research

Research work presented in this thesis for standalone and interlinked ac microgrids has shown potential benefits in terms of cost saving and performance improvement of the supply system. These are certainly strong motivations for pushing forward its continuation, and for that, the following are possible topics recommended for future investigation.

- The characteristic or cost-based droop schemes proposed for standalone microgrids have been shown to reduce generation costs when active and reactive power generations are considered. Although the same concepts can be applied to harmonic power sharing, its realization might be different. It is thus appropriate

to investigate related schemes for standalone microgrids when subjected to harmonic power sharing and other ancillary services.

- The characteristic-based power sharing schemes are discussed with the DGs assumed to be of either the internal combustion engine or dispatchable renewable type. The same characteristic functions can be used to represent most DGs powered by sources, but might be different for DGs powered or complemented by specific types of storage mediums. Modifications to the characteristic functions and proposed droop schemes must hence be designed, where necessary.
- Stable operation of microgrid has been proven for the proposed cost-based schemes through experimental testing and stability expressions. Where of interest, mathematical derivation and parametric study of complete system can be performed with more power component included. The models obtained can subsequently be used for control designing purposes.
- The research work presented here for interlinked microgrids has focused mainly on the steady-state droop operational mode of the interlinking converters when tying two microgrids together. During transient, the droop principles can no longer be applied, inferring that additional transitional schemes need to be developed for the interlinking converters. This is surely an interesting topic for investigation.
- Small-signal stability of interlinked hybrid microgrids is another important research topic for consideration. The analytical conclusions drawn can help with parameter tuning over a wide range of stable operating modes.

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Appendix-A

Small-Signal Stability Model of Droop Controlled Converters

In this section, state-space averaged models of the traditional droop and cost-based droop schemes are developed for stability study. The difference between the traditional and cost-based droop controlled converters is solely concentrated in their droop expressions, while the rest of the system remains unchanged for the two types of droop schemes. Therefore, earlier discussed results (reviewed in Chapter 2) for the traditional droop scheme can be borrowed for studying stability of the proposed cost-based schemes. The research findings on the traditional scheme concluded that droop gains of DGs are the stability contributing factors. Non-minimal state space model of the traditional droop and cost-based droop controlled converters has therefore been developed to compare their stability contributing factors.

Based on Lyapunov's linearization method, all the equations have been linearized and finite matrix is formed for each scheme. A general state-space representation of a linearized DG system is given by (1).

$$\Delta \dot{x} = A_{DG} \Delta x + B_{DG} u \quad (1)$$

Definition of notations and assumptions made in deriving the expressions are given below,

- Upper case letters represents RMS values and lower case letters represents instantaneous values.

- Notation “ Δ ” represents the normalized variable and dot “ $\dot{\cdot}$ ” represents the derivative with respect to time.
- Letter “ Δx ” and “ $\dot{\Delta x}$ ” represent matrix for “normalized state-space vector” and “derivative of state-space vector with respect to time”, respectively.
- DC voltage has been assumed constant.
- Model is subject to inclusion of phase-lock loop (PLL).

Fig. A1 shows the complete block diagram of a typical droop controlled converter with power stage and controllers. Linearized state-space expressions of all these components are developed and then finite matrix is formed for each scheme.

Fig. A1. Block diagram showing droop controlled converter

A1. Converter Model

Linearized differential equations of converter power stage are developed in this section, which include inductor current (Δi_{Lfdq}), output voltage (Δv_{cfdq}) and output current (Δi_{odq}). All the equations have been converted into synchronous reference frame.

Filter Inductor Current

Linearized differential equation of inductor current in synchronous reference frame (Δi_{Lfdq}) is developed as in (2).

$$\begin{bmatrix} \Delta \dot{i}_{Lfd} \\ \Delta \dot{i}_{Lfq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} \Delta i_{Lfd} \\ \Delta i_{Lfq} \end{bmatrix} + \frac{v_{dc}}{L_f} \begin{bmatrix} \Delta d_d \\ \Delta d_q \end{bmatrix} - \frac{1}{L_f} \begin{bmatrix} \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix} \quad (2)$$

Filter Capacitor Voltage /Output Voltage

Linearized differential equation of converter output or filter capacitor voltage in synchronous reference frame (Δv_{odq}) is developed as in (3).

$$\begin{bmatrix} \Delta \dot{v}_{cfd} \\ \Delta \dot{v}_{cfq} \end{bmatrix} = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} \begin{bmatrix} \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix} + \frac{1}{c_f} \begin{bmatrix} \Delta i_{Lfd} \\ \Delta i_{Lfq} \end{bmatrix} - \frac{1}{c_f} \begin{bmatrix} \Delta i_{od} \\ \Delta i_{oq} \end{bmatrix} \quad (3)$$

Output Current

Linearized differential equation of converter output current in synchronous reference frame (Δv_{odq}) is developed as in (4).

$$\begin{bmatrix} \Delta \dot{i}_{od} \\ \Delta \dot{i}_{oq} \end{bmatrix} = \begin{bmatrix} -\frac{R_t}{L_t} & \omega \\ -\omega & -\frac{R_t}{L_t} \end{bmatrix} \begin{bmatrix} \Delta i_{od} \\ \Delta i_{oq} \end{bmatrix} + \frac{1}{L_t} \begin{bmatrix} \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix} - \frac{1}{L_t} \begin{bmatrix} \Delta v_{mgd} \\ \Delta v_{mgq} \end{bmatrix} \quad (4)$$

State-space representation of the converter power stage is deduced from (2), (3) and (4) and expressed by (5), and in general form by (6).

The state-space model given in (5) and (6) represents the power stage of the converter, which is subject to further derivation of gain " Δd_{dq} " and addition of more state variables from the control feedback loops shown in Fig. A1. Linearized differential equations of variables in control feedback loops are developed in next section.

$$\begin{aligned}
\begin{bmatrix} \Delta \dot{i}_{Lfd} \\ \Delta \dot{i}_{Lfq} \\ \Delta \dot{i}_{od} \\ \Delta \dot{i}_{oq} \\ \Delta \dot{v}_{od} \\ \Delta \dot{v}_{oq} \end{bmatrix} &= \begin{bmatrix} 0 & 0 & 0 & -\omega & 0 & 0 & -\frac{1}{L_f} & 0 \\ 0 & 0 & \omega & 0 & 0 & 0 & 0 & \frac{1}{L_f} \\ 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \begin{bmatrix} \Delta i_{Lfd} \\ \Delta i_{Lfq} \\ \Delta i_{od} \\ \Delta i_{oq} \\ \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix} + \\
\begin{bmatrix} 0 & 0 & \frac{v_{dc}}{L_f} & \frac{v_{dc}}{L_f} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta d_d \\ \Delta d_q \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_t} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_t} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \Delta v_{mgd} \\ \Delta v_{mgq} \\ 0 \\ 0 \end{bmatrix} \quad (5)
\end{aligned}$$

$$\Delta \dot{x} = A_C \Delta x + B_C \Delta d_{dq} + B_C \Delta v_{mgdq} \quad (6)$$

A2. Controller Model

The controller model or control feedback loops comprise of current controller, voltage controller, droop controller and power measurement block with averaging filter, as shown in Fig. A1. Except the droop controller, the remaining control blocks are common in the traditional and cost-based droop schemes. Linearized equations of the variables associated with these common blocks are given below.

Current Controller

Linearized equation of the current controller output variable $\Delta v_{dq_ref} = \Delta d_{dq} * v_{dc}$ is developed as in (9).

$$\begin{aligned}
\Delta d_d &= \frac{k_{ip}}{v_{dc}} \Delta i_{Lfd_ref} - \frac{k_{ip}}{v_{dc}} \Delta i_{Lfd} + \frac{k_{ii}}{v_{dc}} \int (\Delta i_{Lfd_ref} - \Delta i_{Lfd}) dt - \frac{\omega_n L_f}{v_{dc}} \Delta i_{Lfq} + \frac{1}{v_{dc}} \Delta v_{od} \\
\Delta d_q &= \frac{k_{ip}}{v_{dc}} \Delta i_{Lfq_ref} - \frac{k_{ip}}{v_{dc}} \Delta i_{Lfq} + \frac{k_{ii}}{v_{dc}} \int (\Delta i_{Lfq_ref} - \Delta i_{Lfq}) dt + \frac{\omega_n L_f}{v_{dc}} \Delta i_{Lfd} + \frac{1}{v_{dc}} \Delta v_{oq} \quad (7)
\end{aligned}$$

$$\Delta d_d = \frac{k_{ip}}{v_{dc}} \Delta i_{Lfd_ref} - \frac{k_{ip}}{v_{dc}} \Delta i_{Lfd} + \frac{k_{ii}}{v_{dc}} \Delta e_{id} - \frac{\omega_n L_f}{v_{dc}} \Delta i_{Lfq} + \frac{1}{v_{dc}} \Delta v_{od}$$

$$\Delta d_q = \frac{k_{ip}}{v_{dc}} \Delta i_{Lq_ref} - \frac{k_{ip}}{v_{dc}} \Delta i_{Lfq} + \frac{k_{ii}}{v_{dc}} \Delta e_{iq} + \frac{\omega_n L_f}{v_{dc}} \Delta i_{Lfd} + \frac{1}{v_{dc}} \Delta v_{oq} \quad (8)$$

$$v_{dc} \begin{bmatrix} \Delta d_d \\ \Delta d_q \end{bmatrix} = \begin{bmatrix} k_{ip} & 0 \\ 0 & k_{ip} \end{bmatrix} \begin{bmatrix} \Delta i_{Lfd_ref} \\ \Delta i_{Lq_ref} \end{bmatrix} - \begin{bmatrix} k_{ip} & 0 \\ 0 & k_{ip} \end{bmatrix} \begin{bmatrix} \Delta i_{Lfd} \\ \Delta i_{Lfq} \end{bmatrix} + \begin{bmatrix} k_{ii} & 0 \\ 0 & k_{ii} \end{bmatrix} \begin{bmatrix} \Delta e_{id} \\ \Delta e_{iq} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_n L_f \\ \omega_n L_f & 0 \end{bmatrix} \begin{bmatrix} \Delta i_{Lfd} \\ \Delta i_{Lfq} \end{bmatrix} + \begin{bmatrix} \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix} \quad (9)$$

Voltage Controller

Similarly, linearized equation of the voltage controller output variable Δi_{Lfdq_ref} is developed as in (12).

$$\Delta i_{Lfd_ref} = k_{vp} \Delta v_{od_ref} - k_{vp} \Delta v_{od} + k_{vi} \int (\Delta v_{od_ref} - \Delta v_{od}) dt - \omega_n C_f \Delta v_{oq}$$

$$\Delta i_{Lfq_ref} = k_{vp} \Delta v_{oq_ref} - k_{vp} \Delta v_{oq} + k_{vi} \int (\Delta v_{oq_ref} - \Delta v_{oq}) dt + \omega_n C_f \Delta v_{od} \quad (10)$$

$$\Delta i_{Lfd_ref} = k_{vp} \Delta v_{od_ref} - k_{vp} \Delta v_{od} + k_{vi} \Delta e_{vd} - \omega_n C_f \Delta v_{oq}$$

$$\Delta i_{Lfq_ref} = k_{vp} \Delta v_{oq_ref} - k_{vp} \Delta v_{oq} + k_{vi} \Delta e_{vd} dt + \omega_n C_f \Delta v_{od} \quad (11)$$

$$\begin{bmatrix} \Delta i_{Lfd_ref} \\ \Delta i_{Lfq_ref} \end{bmatrix} = \begin{bmatrix} k_{vp} & 0 \\ 0 & k_{vp} \end{bmatrix} \begin{bmatrix} \Delta v_{od_ref} \\ \Delta v_{oq_ref} \end{bmatrix} - \begin{bmatrix} k_{vp} & 0 \\ 0 & k_{vp} \end{bmatrix} \begin{bmatrix} \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix} + \begin{bmatrix} k_{vi} & 0 \\ 0 & k_{vi} \end{bmatrix} \begin{bmatrix} \Delta e_{vd} \\ \Delta e_{vq} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_n C_f \\ \omega_n C_f & 0 \end{bmatrix} \begin{bmatrix} \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix} \quad (12)$$

Power Measurement and First Order Filter

Linearized differential equation of the power measurement block combined with the averaging filter is developed as in (13).

$$\begin{bmatrix} \dot{\Delta P} \\ \dot{\Delta Q} \end{bmatrix} = \begin{bmatrix} -\omega_c & 0 \\ 0 & -\omega_c \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} + \begin{bmatrix} \omega_c I_{odn} & \omega_c I_{oqn} & \omega_c V_{odn} & \omega_c V_{oqn} \\ \omega_c I_{oq} & -\omega_c I_{odn} & -\omega_c V_{oqn} & \omega_c V_{odn} \end{bmatrix} \begin{bmatrix} \Delta v_{odq} \\ \Delta i_{odq} \end{bmatrix} \quad (13)$$

In the following section, linearized equations of the droop controllers are developed for all schemes. Subsequently, the controllers and power stage model of the converter are combined to obtain the complete state-space model.

A3. Traditional Droop Controlled Converter

Frequency and voltage reference equations of the traditional droop scheme are rewritten in (14) and (15).

$$\omega_{ref} = \omega_{max} - mP; \quad m = \frac{\omega_{max} - \omega_{min}}{P_{rated}} \quad (14)$$

$$V_{oref} = V_{max} - nQ; \quad n = \frac{V_{max} - V_{min}}{Q_{rated}} \quad (15)$$

Equation (14) and (15) are then linearized to obtain (16) and (17) for frequency and voltage reference.

$$\Delta\omega_{ref} = \dot{\Delta\delta} = -m \Delta P \quad (16)$$

$$\Delta V_{oref} = \Delta v_{odref} = -n \Delta Q;$$

$$\begin{bmatrix} \Delta v_{odref} \\ \Delta v_{oqref} \end{bmatrix} = \begin{bmatrix} 0 & -n \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (17)$$

Complete state-space model of the traditional droop controlled converter can be expressed by (18), and in general form by (19) after following substitutions,

- Frequency in (16), active and reactive power in (13) are added as control variables in the converter power stage model (5).
- Droop controller voltage reference in (17), current and voltage controller variables derived in (9) and (12) are substituted in the converter power stage model (5).

$$\begin{aligned}
& \begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta P} \\ \dot{\Delta Q} \\ \dot{\Delta i_{Lfd}} \\ \dot{\Delta i_{Lfq}} \\ \dot{\Delta i_{od}} \\ \dot{\Delta i_{oq}} \\ \dot{\Delta v_{od}} \\ \dot{\Delta v_{oq}} \end{bmatrix} = \begin{bmatrix} 0 & -m & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & \frac{-nk_{vp}k_{ip}}{L_f} & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1-k_{vp}k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & 0 & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1-k_{vp}k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta P \\ \Delta Q \\ \Delta i_{Lfd} \\ \Delta i_{Lfq} \\ \Delta i_{od} \\ \Delta i_{oq} \\ \Delta v_{od} \\ \Delta v_{oq} \end{bmatrix} + \\
& + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{k_{vi}k_{ip}}{L_f} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{k_{vi}k_{ip}}{L_f} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ \Delta e_{vd} \\ \Delta e_{vq} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{k_{ii}}{L_f} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{k_{ii}}{L_f} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ \Delta e_{id} \\ \Delta e_{iq} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \\
& \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_t} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_t} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \Delta v_{mgd} \\ \Delta v_{mgq} \\ 0 \\ 0 \end{bmatrix}
\end{aligned} \tag{18}$$

$$\Delta \dot{x} = A_{DG} \Delta x + B_v \Delta e_{vdq} + B_i \Delta e_{idq} + B_{mg} \Delta v_{mgdq} \tag{19}$$

A4. Cost-Based Droop Scheme (Section 3.4)

Linearization of Converter Cost-Function

The simplified cost-function of DG can be represented by (20).

$$C(P) = K(a + bP + cP^2) \tag{20}$$

After taking the differential,

$$\frac{\partial C(P)}{\partial P} = Kb + 2KcP \tag{21}$$

Linearized equation for the cost-function of DG can be derived in (22) after following steps.

$$\begin{aligned}
\partial C(P + \Delta P) &= \partial C + \frac{\partial C(P)}{\partial P} \Delta P \\
\partial C(P + \Delta P) - \partial C &= \frac{\partial C(P)}{\partial P} \Delta P \\
\Delta C(\Delta P) &= (Kb + 2KcP)\Delta P ; P = P_{rated} \\
\Delta C(\Delta P) &= (Kb + 2KcP_{rated})\Delta P
\end{aligned} \tag{22}$$

Linearization of Cost-Based Droop Equations

Frequency reference equation of the cost-based droop scheme used in Section 3.4 is re-written by (23).

$$\begin{aligned}
f_{ref} &= f_{max} - mP + \Delta f_{off} = f_{max} + mP + K_f C''_{ref}; m = \frac{f_{max} - f_{min}}{P_{rated}} \\
\omega_{ref} &= \omega_{max} - mP + \Delta f_{off} = \omega_{max} + mP + K_f C''_{ref}; m = \frac{\omega_{max} - \omega_{min}}{P_{rated}}
\end{aligned} \tag{23}$$

In (23), K_f is constant and C''_{ref} is the cost-function of reference DG. The reference cost-function C''_{ref} need to be linearized, which can be referred from the generic linearized cost-function equation (22), and written by (24).

$$\Delta C''_{ref}(\Delta P) = \left(\frac{Kb}{P_{rated}} + \frac{2KcP_{rated}}{P_{rated}} \right) \Delta P = \left(\frac{Kb}{P_{rated}} + 2Kc \right) \Delta P \tag{24}$$

Linearized frequency reference can be expressed by (25) after linearizing equation (23) and solving it with the equation (24).

$$\Delta \omega_{ref} = \left(-m + \frac{K_f Kb}{P_{rated}} + 2K_f Kc \right) \Delta P \tag{25}$$

Similarly, linearized voltage reference equation of the cost-based droop scheme can also be derived, as in (26).

$$\Delta V_{ref} = \left(-n + \frac{K_v Kb}{Q_{rated}} + 2K_v Kc \right) \Delta Q$$

$$\begin{bmatrix} \Delta v_{odref} \\ \Delta v_{oqref} \end{bmatrix} = \begin{bmatrix} 0 & -n + \frac{K_V K_b}{Q_{rated}} + 2K_V K_c \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (26)$$

Finite matrix of the cost-based droop controlled converter is then deduced in (27) after following substitutions,

- Frequency in (25), active and reactive power in (13) are added as control variables in the converter power stage model (5).
- Droop controller voltage references in (26), current and voltage controller variables derived in (9) and (12) are substituted in the converter power stage model (5).

$$A_{DG} = \begin{bmatrix} 0 & -m + \frac{K_f K_b}{P_{rated}} + 2K_f K_c & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & 0 & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1-k_{vp}k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & \frac{(-n + \frac{K_V K_b}{Q_{rated}} + 2K_V K_c)k_{vp}k_{ip}}{L_f} & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1-k_{vp}k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \quad (27)$$

A5. Cost-Based Droop Scheme with Accurate Cost Curve Tracing (Section 3.5)

Linearization of Cost-Based Droop Equations

Frequency and voltage reference equations of the cost-based droop scheme used in Section 3.5 are re-written by (28) and (29), respectively.

$$f_{ref} = f_{max} - m_c C''(P); m_c = \frac{f_{max} - f_{min}}{C''_{P,max}}$$

$$\omega_{ref} = \omega_{max} - m_c C''(P); m_c = \frac{\omega_{max} - \omega_{min}}{C''_{P,max}} \quad (28)$$

$$V_{ref} = V_{max} - n_c C''(Q); n_c = \frac{V_{max} - V_{min}}{C_{Q,max}} \quad (29)$$

In (28) and (29), m_c and n_c are constants, whereas $C''(P)$ and $C''(Q)$ represent the normalized cost-functions of DGs. Referred from the generic linearized cost-function (22), $C''(P)$ can be linearized as in (30)

$$\Delta C''(\Delta P) = \left(\frac{Kb}{P_{rated}} + \frac{2KcP_{rated}}{P_{rated}} \right) \Delta P = \left(\frac{Kb}{P_{rated}} + 2Kc \right) \Delta P \quad (30)$$

$$\Delta C''(\Delta Q) = \left(\frac{Kb}{Q_{rated}} + \frac{2KcQ_{rated}}{Q_{rated}} \right) \Delta Q = \left(\frac{Kb}{Q_{rated}} + 2Kc \right) \Delta Q \quad (31)$$

Linearized frequency and voltage reference equations (32) and (33) can be obtained by linearizing equations (28) and (29) and solving with equations (30) and (31).

$$\Delta \omega_{ref} = -m_c \Delta C''(\Delta P) = -m_c \left(\frac{Kb}{P_{rated}} + 2Kc \right) \Delta P$$

$$\Delta \omega_{ref} = -m_c \left(\frac{Kb}{P_{rated}} + 2Kc \right) \Delta P \quad (32)$$

$$\Delta V_{ref} = \Delta v_{dref} = -n_c \left(\frac{Kb}{Q_{rated}} + 2Kc \right) \Delta Q$$

$$\begin{bmatrix} \Delta v_{odref} \\ \Delta v_{oqref} \end{bmatrix} = \begin{bmatrix} 0 & -n_c \left(\frac{Kb}{Q_{rated}} + 2Kc \right) \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (33)$$

Finite matrix of the cost-based droop controlled converter (used in section 3.5) is deduced in (34) after following substitutions,

- Frequency in (32), active and reactive power in (13) are added as control variables in the converter power stage model (5).
- Droop controller voltage references in (33), current and voltage controller variables derived in (9) and (12) are substituted in the converter power stage model (5) .

$$A_{DG} = \begin{bmatrix} 0 & -m_c(\frac{Kb}{P_{rated}} + 2Kc) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & 0 & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1-k_{vp}k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & \frac{-n_c(\frac{Kb}{Q_{rated}} + 2Kc)k_{vp}k_{ip}}{L_f} & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1-k_{vp}k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \quad (34)$$

A6. Cost-Prioritized Droop Scheme (Section 4.2)

Linearization of Cost-Prioritized Droop Equations

Frequency and voltage reference equations of the cost-prioritized droop scheme used in Section 4.2 are re-written by (35) and (36), respectively.

$$\omega_{ref} = \omega_{max} - m_x P ; m_L = \frac{\omega_{x,max} - \omega_{x,min}}{P_{max}} \quad (35)$$

$$V_{ref} = V_{max} - n_x Q ; n_L = \frac{V_{x,max} - V_{x,min}}{Q_{max}} \quad (36)$$

Equation (35) and (36) can be linearized as follow:

$$\Delta\omega_{ref} = -m_L \Delta P \quad (37)$$

$$\Delta V_{oref} = \Delta v_{odref} = -n_L \Delta Q$$

$$\begin{bmatrix} \Delta v_{odref} \\ \Delta v_{oqref} \end{bmatrix} = \begin{bmatrix} 0 & -n_L \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (38)$$

Finite matrix of the cost-prioritized droop controlled converter is deduced in (39) after following substitutions,

- Frequency in (37), active and reactive power in (13) are added as control variables in the converter power stage model (5).
- Droop controller voltage references in (38), current and voltage controller variables in (9) and (12) are substituted in the converter power stage model (5).

$$A_{DG} = \begin{bmatrix} 0 & -m_L & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 & \omega_c V_{odn} & \omega_c V_{oqn} & \omega_c I_{odn} & \omega_c I_{oqn} \\ 0 & 0 & -\omega_c & 0 & 0 & -\omega_c V_{oqn} & \omega_c V_{odn} & \omega_c I_{oq} & -\omega_c I_{odn} \\ 0 & 0 & 0 & \frac{-k_{ip}}{L_f} & -\omega - \omega_n & 0 & 0 & \frac{1-k_{vp}k_{ip}}{L_f} & \frac{-\omega_n C_f k_{ip}}{L_f} \\ 0 & 0 & \frac{-n_L k_{vp} k_{ip}}{L_f} & \omega + \omega_n & \frac{-k_{ip}}{L_f} & 0 & 0 & \frac{\omega_n C_f k_{ip}}{L_f} & \frac{1-k_{vp}k_{ip}}{L_f} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_t}{L_t} & \omega & \frac{1}{L_t} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega & -\frac{R_t}{L_t} & 0 & \frac{1}{L_t} \\ 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & 0 & 0 & 0 & \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix} \quad (39)$$

Finite matrices delivered in this section are used in Sections 3.6.1 and Section 4.3.1 for stability discussion.