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Design and Control of Storage Systems for Voltage Source Controlled Autonomous Microgrids

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Abstract—Self-sustainable autonomous microgrids with 100% converter-connected generation are most suitable for powering remote areas without impacting the environment. This work focuses on the regulation aspect of such islanded microgrids by sizing and controlling energy storage systems to support the renewable energy-based microgrids. Each generation unit in the microgrid acts as a voltage-source that contributes to frequency and voltage regulation, wherein the regulation is achieved by a modified droop control that emulates the inertia property of synchronous machines. The size of energy storage systems that support this task is estimated based on the allowable regulation standard and control scheme. The designed storage and control are validated with the help of real-time simulation.

Index Terms—Droop control, textscess sizing, Frequency response, Islanded microgrids, Virtual inertia.

I. INTRODUCTION

Alongside the tremendous growth of smart technologies in the power sector, access to electricity still remains a concern among 1.1 billion people. Distributed generation (DG) technologies such as the solar photovoltaics (PV), wind turbines, biomass or gas-based microturbines (MT), and diesel generators play an extensive role in powering these remote areas. Diesel genertors serve as the obvious solution for enabling dispatchability in the standalone microgrids with converter-connected renewable generation. Hence, this work focusses on the sizing and control of energy storage systems (ESS) to facilitate self-sustainability of 100% converter-based islanded microgrids.

As the microgrid is solely converter-based the generation units (GUs) must act as voltage sources that respond to the changing load. These units respond to the load variation by changing the amplitude and frequency of the output voltage and are hence called Vf responsive units. The control of Vf responsive units comprises of three layers based on the time of response: primary regulation control, secondary load-following control, and tertiary market control [1]. Regulation control may be realized by cooperative schemes such as current-sharing scheme [2], master-slave scheme [3], distributed control [4], or a decentralized droop control [5]. Although these strategies have their own set of merits and demerits [1], a strategy that is devoid of any communication requirement is most suited for

Fig. 1: Schematic of the autonomous microgrid.

the application. Hence, the droop control strategy is chosen in this approach to estimate the ESS size and design its control.

A. Aspects of Inverter Control

The concept of droop is practised in traditional power systems where the governor power set point of the synchronous generator is drooped based on the generator speed measurement. A similar frequency response technique can be emulated in the inverter control by setting the active power reference of the system based on the frequency measurement at the inverter terminal. In [5], the authors have demonstrated how the droop concept can be applied to control inverters in the voltage-source mode. It allows power sharing among the inverters by adjusting the voltage amplitude and frequency reference of the inverter. The droop concept therefore trades-off the frequency and voltage regulation for the power sharing accuracy [6].

Recently, islanded microgrids have been studied for droop scheduling [7], adaptive droop variation, and the effect of droop variation on the stability of the system [8]. While studying islanded microgrids, these works assume an infinite source providing a constant DC voltage to the inverters. However, in practical systems the DC-link voltage is subject to variations unless there is a controlled DC-DC converter that maintains the constant DC-link voltage. In this work, we model the islanded microgrid as shown in fig. 1 along with the DC side of the inverter and the DC-DC converter is controlled to maintain a constant DC-link voltage.

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Islanded microgrids are inherently low-inertia power systems. Inertia property resists the sudden change in system conditions and controls the rate-of-change-of-frequency (ROCOF) on the occurrence of a contingency. Absence of inertia makes the microgrid vulnerable to transients, where the ROCOF exceeds the designed limit for which the protection system is designed, leading to unnecessary tripping. For the converter-connected units to contribute to inertia, the droop control has been modified in this work to provide inertia response (IR), in addition to the primary frequency response (PFR). Virtual inertia (VI) control may be implemented with a power-frequency response technique in the current control mode [9]. Other control techniques implement VI control by modelling the synchronous generator equations in the inverter control or by modelling the swing equation in the inverter control [10]. In this work, we modify the droop control to emulate VI with a swing-based model.

B. ESS Sizing for Islanded Microgrids

In islanded microgrids, the participation of every GU in the frequency response is limited by its flexibility, while the flexibility of each renewable unit is restricted by its ESS design. The ESS requirement is estimated with the required balancing power in the different time zones. The authors of [11] apply the discrete fourier transform to decompose balancing power based on the time scale. ESS sizing for balancing the renewable intermittency is widely discussed in researches such as [11]–[13] previously.

Reference [12] discusses the adequacy evaluation of a PV-based islanded microgrid in a minute-scale in terms of reliability indices. However, since the microgrid considered in this work has a conventional synchronous generator support, sizing of the smaller regulation time scale is not discussed. In our work, we focus on the regulation time-scale balancing power that is required for PFR and IR. Researches like [13] address the ESS sizing problem along with their placement. The ESS placement problem is significant in cases where some area of the power system is supported by synchronous generators, while the rest of the system is a low-inertia system. However, in the case of 100% converter connected system with fewer units, the microgrid stiffness is uniformly low and the placement of ESS does not affect the performance significantly.

C. Aims and Contributions

This paper aims to utilize ESS to support the regulation and stability enhancement of a standalone microgrid. A regulation control scheme based on droop control is adopted and modified to serve as an inertia support to the 100% converter-connected system. The ESS requirement to meet a given set of steady-state conditions and stability criteria is estimated. Finally, the control is validated by means of real-time simulation using the OPAL-RT simulator.

II. INVERTER DROOP AND VIRTUAL INERTIA CONTROL

A. Droop controller

Droop control implements a linear relationship between Pf and QV in the phasor domain. Thus, the inverter terminal

(a) Inverter control scheme.

(b) Droop control.

(c) Inner voltage controller.

(d) Inner current controller.

Fig. 2: Inverter droop control schematic.

voltage frequency and magnitude reference are given by the droop control. It may be implemented with the help of a droop block, a proportional integral (PI) voltage controller, and a PI current controller whose control schematics are presented in fig. 2 [14].

The droop block measures the averaged values of real and reactive power given by (1) and (2) respectively. The active and reactive power measurements P and Q are computed from the inverter output current i_o and output voltage v_o . The measured voltages and currents are represented as dq components (v_{od}, v_{oq}) and (i_{od}, i_{oq}) respectively. In order to avoid the harmonics in the measurements from propagating to the control, a low pass filter (LPF) with corner frequency ω_c is provided. The frequency and the voltage references are then generated based on the droop laws (3) and (4) respectively, where ω_n and V_n represent the nominal frequency and voltage.

$$P = \frac{\omega_c}{s + \omega_c} (v_{od}i_{od} + v_{oq}i_{oq}) \quad (1)$$

$$Q = \frac{\omega_c}{s + \omega_c} (v_{od}i_{oq} - v_{oq}i_{od}) \quad (2)$$

$$\omega = \omega_n - m_p P \quad (3)$$

$$v_{od}^* = V_n - n_q Q \quad (4)$$

The inverter is connected to the bus through an LCL filter with components $(r_f, L_f), C_f, (r_c, L_c)$. The voltage reference generated from the droop controller, (v_{od}^*, v_{oq}^*) is fed to the inner voltage loop controller to generate the output current reference for the inverter given by (5)-(8). The corresponding PI control parameters are K_{pv} and K_{iv} .

$$\phi_d = \int (v_{od}^* - v_{od}) \quad (5)$$

$$\phi_q = \int (v_{oq}^* - v_{oq}) \quad (6)$$

$$i_{ld}^* = F i_{od} - \omega_n C_f v_{oq} + K_{pv} (v_{od}^* - v_{od}) + K_{iv} \phi_d \quad (7)$$

$$i_{lq}^* = F i_{oq} + \omega_n C_f v_{od} + K_{pv} (v_{oq}^* - v_{oq}) + K_{iv} \phi_q \quad (8)$$

The current reference generated from the PI current control loop, (i_{ld}^*, i_{lq}^*) , is fed to the inner voltage control loop to generate the inverter output voltage reference before the LCL filter as given by (9)-(12). The corresponding PI control parameters are K_{pc} and K_{ic} .

$$\nu_d = \int (i_{ld}^* - i_{ld}) \quad (9)$$

$$\nu_q = \int (i_{lq}^* - i_{lq}) \quad (10)$$

$$v_{id}^* = -\omega_n L_f i_{lq} + K_{pc} (i_{ld}^* - i_{ld}) + K_{ic} \nu_d \quad (11)$$

$$v_{iq}^* = \omega_n L_f i_{ld} + K_{pc} (i_{lq}^* - i_{lq}) + K_{ic} \nu_q \quad (12)$$

B. Virtual Inertia Control

The concept of VI control is that the rate of power injection of the GU is increased when the ROCOF increases in the negative direction and vice versa. This effect is achieved by altering the rate of injected or absorbed power of the unit when the GU is current-controlled [9]. This concept may be implemented in the inverter control by simply adding a rate limiter to the controlled frequency reference signal to curtail the ROCOF to a preset limit. In a voltage source controlled-inverter, inertia control is implemented by using an LPF to slow down the speed of response of the system to contingencies in [6]. If the active power output of the inverter is measured with the help of a low pass filter with time constant $T_f = 1/\omega_c$, the droop equation (13) may be re-arranged as (14) to compute the equivalent inertia and damping of the droop controller as given by (15), where, P_b is the base power of the GU.

$$\omega_i^* = \omega_n - m_p \left(\frac{P}{(1 + T_f s)} - P_b \right) \quad (13)$$

$$P_b - P = \frac{T_f}{m_p} s(\omega_i^*) + \frac{\omega_i^* - \omega_n}{m_p} \quad (14)$$

$$J = \frac{T_f}{m_p}; D = \frac{1}{m_p} \quad (15)$$

VI contribution by the LPF of droop control in (14) is not fully controllable and the ratio J/D is constant for a system. The inability to independently control inertia of the unit is overcome by using a swing-equation based model for the VI control. Hence, the VI control may be called the virtual synchronous generator control. Since there is no mechanical turbine power in an inverter, P_{in} can be regarded as the virtual input power given by (16). The swing equation can be written as (17) and the modified frequency reference can be derived as (18). The swing-based emulation may be implemented for Vf responsive controllers. However, there may be problems of numerical instability along with the oscillatory stability issues that may arise due to the improper tuning of J and D parameters. Thus, the droop and inertia values chosen in this work were analyzed with the help of root locus plots as in [6] however the analysis results are not presented as it is out of the scope of this paper.

$$P_{in} = P - \frac{(\omega_n - \omega)}{m_p} \quad (16)$$

$$P_{in} - P = J\omega \frac{d\omega}{dt} \quad (17)$$

$$\omega_n = \omega + \int -\frac{(\omega_n - \omega)}{Jm_p} + P_{in} - P \quad (18)$$

III. ESS SIZING FOR PRIMARY FREQUENCY RESPONSE

The 2030.7-2017 IEEE standard for microgrid specification [15] specifies that the allowable standard for microgrids. In this work, the ESS is sized according to the standard that the allowable frequency deviation is ± 0.2 Hz and that the PFR has to act within 30 seconds when the frequency deviation crosses the ± 0.02 Hz deadband and should be capable of providing PFR for at least 15 minutes [9].

For a frequency deviation range of ± 0.02 Hz to ± 0.2 Hz, the ESS has to supply/draw its rated power, i.e. 1 per unit (p.u.). Hence the droop constant in p.u. m_{ess} can be given by (19). The autonomous microgrid consists of 3 inverters fed from a DC bus by the combination of a DG source and 3 loads of RL, RC and RL respectively [6]. The AC side data of the system may be obtained from [6], [14]. To size the ESS for PFR, knowledge of the worst system disturbance P_{dist} is vital. In this case, we consider a 27kW step load change as the worst disturbance [14]. For this disturbance, to maintain the frequency deviation within allowable levels, the required

frequency/power characteristic λ_{reqd} of the system is given by (20).

$$m_{ess} = (0.2 - 0.02)/50 = 0.0036 \quad (19)$$

$$\lambda_{reqd} = P_{dist}/-0.2 \quad (20)$$

$$P_{ess} = m_{ess} f_0 \lambda_{reqd} \quad (21)$$

$$E_{ess} = \frac{t_{reqd} P_{ess} \eta_c}{3600} + \frac{t_{reqd} P_{ess}}{3600 \eta_d} \quad (22)$$

From the required λ_{reqd} , the power (MW) and energy rating (MWh) of the ESS can be computed from (21) and (22) respectively, where the ESS charging and discharging efficiency are $\eta_c = 0.9$ and $\eta_d = 0.9$ respectively and t_{reqd} is the 15 minutes of required PFR control action. This calculation also means that for any frequency deviation larger than ± 0.2 Hz, the balancing power supplied or drawn by the ESS will be limited by its rating and the droop value will vary accordingly.

IV. ESS SIZING FOR INERTIAL RESPONSE

IR control can be viewed as a frequency derivative control or an integral control of power to calculate the frequency set point. The inertia support provided by the ESS, J_{ESS} can be estimated as 2, because the ESS has to be designed to deliver its rated power (1 p.u.) for ± 0.5 Hz/s ROCOF. The required inertia constant of the ESS can be calculated by (23). For a given J_{ESS} , the H_{ESS} can be estimated by (25), where P_{IR} is the power injected by ESS in p.u. given by (24).

$$H_{reqd} = P_{dist} \left(\frac{f}{2} \right) \left(\frac{df}{dt} \right)^{-1} \quad (23)$$

$$p_{IR} = J_{ESS} (df/dt) \quad (24)$$

Until the allowable ROCOF limit, the ESS is designed to supply the rated power. When the ROCOF value exceeds ± 0.5 Hz/s, the power output of the ESS is curtailed to its rated value.

$$H_{ess} = \begin{cases} \frac{f}{2} J_{ESS}; & p_{IR} \leq 1; \quad \frac{df}{dt} \leq 0.5 \text{ Hz/s} \\ \frac{f}{2} \left(\frac{df}{dt} \right)^{-1} & p_{IR} > 1 \quad \frac{df}{dt} > 0.5 \text{ Hz/s} \end{cases} \quad (25)$$

Hence, the ESS size P_{ess} can be estimated by (26), where S_{sys} is the system power rating. The energy required may be computed by (27), where the maximum time period for IR control action would extend until the PFR control takes over. Hence, it would last for a maximum of 30 seconds.

$$P_{ess} = S_{sys} \frac{H_{reqd}}{H_{ess} - H_{reqd}} \quad (26)$$

$$E_{ess} = \int_0^{30} \eta_c P_{IR} dt + \int_0^{30} \frac{P_{IR}}{\eta_d} dt \quad (27)$$

V. SIMULATION RESULTS

In this work, the microgrid system presented in section I is considered to size the ESS for PFR and IR control using droop and virtual inertia control respectively. The system data for the AC side of the microgrid may be obtained from [14]. The DC side of each inverter is equipped with a

10kWp solar PV system working at 320Vdc. Three Lithium-ion batteries of 265V, 50 Ah capacity are connected in parallel and a super capacitor bank with 10 super-caps 300V, 5.8F is connected with each solar PV system to balance out the solar intermittency. The DC-DC converter maintains a constant DC-link voltage of 400V using a PI control to set the battery and super-capacitor reference current. The component of the current reference greater than 5Hz cut-off is allocated to the super-capacitor as it has a high power rating and a low energy rating device, while the battery has a high energy rating and a low power rating device. In case of multiple batteries, the power is shared by a DC droop control scheme.

Table I presents the design of ESS computed according to the described sizing procedure in the previous sections. It can be inferred from the table that the PFR directly impacts the frequency deviation and the ESS size for PFR has a low power and high energy rating compared to the that of IR. IR control impacts the RoCoF and the f_{min} or Nadir frequency. The power rating required for IR is extremely high and hence comes the need for super capacitors with extremely high power ratings. However, these sizes were computed with the distribution system frequency standard. The restrictions on frequency variations for islanded microgrids can be more liberal and is subjective. Thus the overall power and energy rating of the system for both the responses combined can be taken as the maximum of the calculated ratings, i.e. 2.7 MW power rating and 12.5kW energy rating.

TABLE I: ESS Sizing for PFR and IR

PFR sizing		IR sizing	
m_{ess}	0.0036 p.u.	J_{ess}	2 p.u.
Δf_{lim}	± 0.2 Hz	$RoCoF_{lim}$	± 0.5 Hz/s
P_{ess}	24.3 kW	P_{ess}	270 kW
E_{ess}	12.22 kWh	E_{ess}	2.43 kWh
Δf	0.204 Hz	Δf	0.32 Hz
$RoCoF$	0.55 Hz/s	$RoCoF$	0.3 Hz/s
f_{min}	49.52 Hz	f_{min}	49.76 Hz

It is to be noted that the ESS size presented in the paper is the total ESS power and energy rating in the system irrespective of the location and type of ESS. This type of generalized sizing allows the use of hybrid energy storage and placement based on the economic benefits. The microgrid simulation results with droop and VI control supported by the estimated size of the ESS is given in fig. 3. Droop control enables power sharing among the inverters. In this case, the inverters are equally sized and the power is shared equally. A load step increase of 1.2 kW is simulated and the frequency deviation, ROCOF and f_{min} are well within the allowable limit. When the PV current varies due to the solar irradiance, the battery kicks in to balance the power. The battery waveforms presented in figure 3 shows the battery current change with PV and load variation. The simulation results presented in this section are verified in offline simulation with MATLAB and Simulink and also in real-time simulation with OPAL-RT as shown in fig. 4.

Fig. 3: Inverter waveforms with modified droop control.

Fig. 4: Realtime validation of droop control.

VI. CONCLUSION AND FUTURE SCOPE

In this work, the ESS design procedure to perform the PFR, i.e. droop control and the IR, i.e. the VI control for a voltage-source controlled islanded microgrid is discussed in detail. The increasing trend of using converter technologies is taken as the inspiration to power a small, decentralized, and self-sustainable power system. Overcoming the adequacy and low-inertia problems of these smaller independent systems builds the grid reliability whether or not they are connected to the main grid. However, this work finds its application in remote areas with no access to grid supply and where fossil fuel based generators may not be encouraged. Line impedance compensation, variation of the droop and inertia control parameters, their impact on microgrid stability and the storage size are some aspects of our future work.

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