Distributed Control Scheme to Regulate Power Flow and Minimize Interactions in Multiple Microgrids

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Abstract—In this paper, a distributed controller is designed for regulating power flow among multiple microgrids in islanded modes with variable renewable energy sources (RESs) while minimizing dynamic interactions. The controller is designed in such a way that it has the capability of gathering information from the neighboring microgrids. This paper also analyzes the dynamic interactions among multiple interconnected microgrids during an islanded mode of operation based on the detailed dynamical model of microgrids. Both modal analysis and non-linear simulations are used to identify the critical issues that might degrade the stability under different operating conditions. From the simulation results, it is found that multiple microgrids operated with local controllers can significantly affect the stability and damping performance. The proposed control scheme is implemented on a test distribution system with multiple microgrids and time-domain simulations are performed to verify its effectiveness of the control scheme. It is found that the designed controller provides excellent performance in minimizing the negative interactions through the regulation of power flow among multiple microgrids in the islanded mode.

Keywords—Multiple microgrids, distributed control, dynamic interactions, islanding operation, power flow regulation.

I. INTRODUCTION

Control of islanded microgrids with non/less inertial renewable energy sources (RESs) is a great challenge for the future power industry. Without a decent control mechanism, serious problems, for example, voltage profile degradation, frequency instability and loss of synchronization can occur in the system. Clustered and agent-based control are proposed in the literature for controlling multiple microgrids [1]–[3]. A cooperative control approach is proposed for controlling voltage by sharing reactive powers among groups of distributed generator (DG) units in [4]. The authors in [5] suggest an optimal reactive power control strategy. However, it has a centralized architecture which requires expensive and reliable communication systems. Recently, a decentralized voltage

control is proposed to minimize distribution power losses in microgrids [6]–[8]. PI controllers are used in [6]–[8] to design voltage and power controllers which work well for a particular system operating conditions. During large disturbances, for example, islanding from grid-connected mode, this type of controllers cannot ensure stable operation as these are not designed by considering the information from neighboring microgrids.

Distributed control is getting popular for controlling clustered microgrids with RESs and energy storage systems (ESSs) as it is significantly difficult to manage and control a large number of distributed generator (DG) units using either centralized or decentralized control. It uses local communication networks and includes the positive features of both centralized or decentralized control while limiting their drawbacks [9]. A self-organizing distributed control for the PV unit is proposed in [10] for power flow control in a distribution system without considering the dynamics of inverters and PV units. The authors in [11] propose a distributed control for power sharing and voltage control in DC microgrids. A model predictive distributed control is proposed in [12] in order to maintain the voltage profile of a multi-area power system within the acceptable bounds. The system nonlinearity and dynamics are completely neglected in [11], [12]. A distributed hierarchical control architecture for automatic generation control is proposed in [13] for large-scale power systems by considering the dynamics of synchronous generators but this is not the case for microgrids in the islanded mode of operations.

When microgrids operate in an islanded mode, the main sources of supplying power to loads are variable RESs rather than synchronous generators. During the grid-connected operation of microgrids, most of the active and reactive power support are provided by the synchronous generator and the excess power from RESs is stored into energy storage systems (ESSs). But during the islanded operation, the amount of active power may be adequate due to the power supply from ESSs and RESs and in this situation, the requirement of reactive power may not be fulfilled. In this case, the contribution of var compensators such as static compensators (STATCOMs) are essential.

This paper investigates the dynamic interactions among different interconnected microgrids. Each microgrid subsystem is integrated with RESs and a STATCOM/ESS and these microgrids negatively interact with each other due to the lack of appropriate power regulation. The amount of exact power regulation can easily be obtained by regulating the active power of ESSs and reactive power of STATCOMs which are

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Fig. 1. Single line diagram of microgrid subsystems.

connected to each microgrid subsystem. The main target of this paper is to develop a distributed control scheme to achieve the desired power regulation by controlling STATCOM/ESS of each microgrid which minimizes negative interactions.

II. MODELING OF MICROGRIDS

An accurate nonlinear dynamical model of a microgrid is significantly important for stability analysis and controller design. The model of a microgrid can have different level of complexities depending upon modeling goals. In this paper full order models of fast acting power electronics converters are considered. Each DG unit is represented by a DC voltage source, a voltage source converter (VSC) and a filter. Fig. 1 shows the single line diagram of two microgrid subsystems connected at i^{th} and j^{th} nodes in an interconnected microgrids. Since DG units are considered as voltage source, V_{dc} is an ideal DC voltage source equivalent to a DG. In Fig. 1, R_f is the equivalent resistance accounting for the switching and transformer losses, L_f is the filter and leakage reactance of the transformer, C_f is the filter capacitance, V_c is the voltage across the filter capacitor, R_t and L_t are line resistance and inductance, respectively.

The mathematical modeling of i^{th} converter in dq frame is given by [14]:

$$\begin{aligned} L_{fi} \dot{I}_{di} &= V_{di} - R_{fi} I_{qi} + \omega_i I_{qi} L_{fi} - V_{tdi} \\ L_{fi} \dot{I}_{qi} &= V_{qi} - R_{fi} I_{di} - \omega_i I_{di} L_{fi} - V_{tdi} \\ L_{ti} \dot{I}_{tdi} &= V_{tdi} - R_{ti} I_{tqi} + \omega_i I_{tqi} L_{ti} - V_{tdi} \\ L_{ti} \dot{I}_{tqi} &= V_{tqi} - R_{ti} I_{tdi} - \omega_i I_{tdi} L_{ti} - V_{tqi} \\ C_i \dot{V}_{di} &= I_{di} - I_{tdi} + \omega_i V_{tqi} C_i - I_{cdi} \\ C_i \dot{V}_{qi} &= I_{qi} - I_{tqi} - \omega_i V_{tdi} C_i - I_{cqi} \end{aligned} \quad (1)$$

where $V_i = \sqrt{V_{di}^2 + V_{qi}^2}$. The real and reactive power power injected by the DG units at the i^{th} bus is given as:

$$\begin{aligned} P_i &= \frac{3}{2} (V_{tqi} I_{tqi} + V_{tdi} I_{tdi}) \\ Q_i &= \frac{3}{2} (V_{tqi} I_{tdi} - V_{tdi} I_{tqi}) \end{aligned} \quad (2)$$

Fast and independent active and reactive power support provided by a STATCOM/energy storage system (ESS) can significantly enhance the performance of microgrids. The main

Fig. 2. STATCOM/ESS control strategy.

components of the STATCOM/ESS shown in Fig. 2 are a normal STATCOM and an ESS. A normal STATCOM is comprised of a coupling transformer, a VSC, and a DC-link capacitor (usually an electrolytic). The DC-link capacitor provides voltage supports for the VSC and the DC chopper. The ESS is comprised of a battery and a bi-directional DC-DC buck-boost converter to control the charging and discharging of the battery. The aim of this module is to store energy in the battery and then deliver that energy to the grid via the DC-link when required. The DC-DC converter operates in buck mode to recharge the battery, whereas boost mode transfers the stored energy to the DC-link.

The mathematical modeling of VSC of the STATCOM is given as [15]:

$$\begin{aligned} L_{si} \dot{I}_{sdi} &= -R_{si} I_{sdi} + I_{sqi} \omega_i + V_{sdi} - V_{dci} s_{di} \\ L_{si} \dot{I}_{sqi} &= -R_{si} I_{sqi} + I_{sdi} \omega_i + V_{sqi} - V_{dci} s_{qi} \\ \dot{v}_{dci} &= -\frac{P_{si}}{C_i v_{dci}} - \frac{v_{dci}}{R_{ci} C_i}, \end{aligned} \quad (3)$$

where v_{dci} is the capacitor voltage, C_{dci} is the DC capacitor, R_{ci} is the internal resistance of the capacitor, and P_{si} is the power supplied by the system to the STATCOM to charge the capacitor. The STATCOM terminal AC voltage is $E_i = k_i v_{dci} \angle \alpha_i$ where α_i is the bus angle of the STATCOM in the reduced network, and $k_i = \sqrt{\frac{3}{8}} m_i$, where m_i is the modulation index.

III. MICROGRID STRUCTURE AND CASE STUDY

The smart operation of a microgrid can be achieved using fast control of hundreds of small individual DG unit. However, it requires real-time information of each DG unit and critical loads. This complexity can be greatly reduced by interconnecting multiple microgrids. A STATCOM with an ESS is connected with a microgrid to control both the active and reactive power. Inverters with ESSs could be used to supply power among interconnected microgrids and tie-line power

Fig. 3. Single line diagram of the test system.

could be controlled by these inverters which are done in this paper. The power transfer among the multiple microgrids can be controlled depending on the magnitude of frequency.

The test system considered in this paper, as shown in Fig. 3, consists of three interconnected microgrids. Each microgrid consists of a PV unit, a fully controlled wind generator (WG), a STATCOM/ESS and mixture of static and dynamic loads. The capacity of the STATCOM is 20 kVA and ESS is 800 Ah. Under normal operating conditions 0.8 MW power is delivered from microgrid 1 to microgrid 3, 0.4 MW from microgrid 2 and 3 and no power between microgrids 2 and 3. A case study is conducted with the conventional controllers which are designed locally without sharing any information with each other [16]. A three-phase fault is applied at the point of common coupling (PCC) in microgrid 3 at 1 s and subsequently cleared after 100 ms. Figure 4 shows the power flow from microgrid 1 to microgrid 3 when only two microgrids (1 and 3) and three microgrids are in operation. It is evident from Fig. 4 that the power flow is oscillatory and take longer time to return to the steady-state condition. The addition of third microgrid reduces the system damping and has negative impacts on the dynamic performance of the system. In order to get the insight of the problem a small-signal analysis is carried out from where it is found that states related to all STATCOM/ESS controllers contribute significantly in the dominating mode.

In a microgrid with thousands of DG units, for example, PV units, wind generators, ESSs and flexible AC transmission system (FACTS) devices, the charging and discharging of the batteries need to be adjusted as the output powers of wind and PV generators are variable due to fluctuations in wind speed and sunlight. It will be difficult to determine and maintain a feasible operating conditions if all the DG units operate independently with decentralized controllers. The centralized control scheme is also not practical and reliable as it requires global collection and exchange of information. Distributed controllers are capable of collecting and exchanging informa-

Fig. 4. Power flow from microgrid 1 to microgrid 3.

Fig. 5. Distributed controller.

tion among different microgrid subsystems and the design of a distributed controller is shown in the following section.

IV. CONTROL STRATEGY

A distributed control approach as shown in Fig. 5 is proposed to handle the numerous distributed energy resource (DER) units. The information among neighboring subsystems can be exchanged using the local communication network which requires less efforts as compared to the centralized control.

The DER units can be represented as follows by linearizing equations (1-3):

$$\begin{aligned}\dot{x}_i &= A_i x_i + B_{u_i} u_i + B_{\omega_i} \omega_i \\ z_i &= C_{z_i} x_i + D_{z u_i} u_i \\ y_i &= C_{y_i} x_i + D_{y \omega_i} \omega_i\end{aligned}\quad (4)$$

where $x_i = [I_{d_i}, I_{q_i}, I_{td_i}, I_{tq_i}, V_{td_i}, V_{tq_i}, I_{ds_i}, I_{qs_i}, V_{dc_i}]$ is the state vector, $u_i = [k_i, \alpha_i]$ is the control input and ω_i is the disturbance input and z_i is the performance output of the i -th agent. The matrices A_i , B_{u_i} , C_{z_i} and C_{y_i} are constant and known, expressing the nominal subsystem model. The matrices B_{ω_i} , $D_{z u_i}$ and $D_{y \omega_i}$ represent unmodeled part of the nonlinear terms, disturbance imposed by the system models, and disturbances due to unmodeled parts. The matrix A_i is calculated at nominal operating points and the change in solar radiation and wind is modeled as a disturbance input to the system.

The STATCOM/ESS controller is depicted in Fig. 2 which provides real power and frequency command to achieve the

desired system response during the transient period. The controller converts the power and frequency commands into pulse-width modulation (PWM) switching signals for the STATCOM/ESS. The designed controller regulates the modulation gain m_i and firing angle (α_i). The firing angle α_i mainly affects the variation of the active power exchanged among different microgrid clusters. Therefore, the function of the active power control is to meet the active power demand of the system during transients. The other output of the controller is the duty cycle ratio m_i which mainly regulates the magnitude of the STATCOM's output voltage and therefore the system voltage. The reference frequency can be calculated from the state of charge (SOC) of the battery. The active power flow among the microgrids are controlled by the voltage phase angle through the regulation of firing angle (α_i) as shown in Fig. 2. Frequency is used as the distinction index to maintain power flow among microgrids both in transient and steady-state conditions.

The proposed controls for the STATCOM/ESS and the inverter are given as [17]:

$$\dot{x}_c = A_c x_c + B_c y(t), \quad u = C_c x_c + D_c y(t), \quad (5)$$

where

$$A_{c_i} = H_{21}^{-T} \left(V_i - [H_{11}^T \quad R_i] \begin{bmatrix} A_i & B_{u_i} \\ C_{y_i} & 0 \end{bmatrix} \begin{bmatrix} G_{11} \\ S_i \end{bmatrix} \right) G_{21}^{-1} \quad (6)$$

$$B_{c_i} = H_{21}^{-T} R_i, \quad C_{c_i} = S_i G_{21}^{-1}, \quad D_{c_i} = 0.$$

where G_{11} , H_{11} , R_i , S_i and V_i are the optimization variables which are determined using the linear matrix inequality (LMI) as described in [17]. It is assumed that each microgrid can only communicate with its nearest neighbors and the Laplacian matrix is chosen as:

$$\mathcal{A} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (7)$$

The objective is to design a distributed controller given in equations (5) and (6) such that the closed system is quadratically stable and achieves a prescribed level of disturbance attenuation in the H_2 norm, i.e., $\|T_{wz}\|_{H_2} < \gamma$. In this paper $\gamma=0.78$.

V. CONTROL DESIGN ALGORITHM AND PERFORMANCE EVALUATION

The design steps of the output-feedback distributed controllers for the nominal system are given below:

- Model the system using equations (1)-(3) and solve it for the steady-state.
- Determine the best input/output variables for the controller from the residues which are the product of system controllability and observability Gramians.
- Linearize the system with the best input and output signals and determine nominal system matrices given in equation (4).
- Reformulate the nonlinear system using the technique proposed in Section IV and determine the other matrices given in equation (4).

Fig. 6. Frequency response in microgrid 3.

Fig. 7. Power flow from microgrid 1 to microgrid 3.

- Solve the linear matrix equality given in [17] to obtain G_{11} , H_{11} , R_i , S_i and V_i in equation (6).
- The controller is given by equations (5) and (6).

The objective of this section is to investigate the performance of the designed controller under various operating conditions on the test system as shown in Fig. 3. The designed controller is implemented by using PSCAD by considering two case studies: (i) severe three-phase fault in one of the microgrids and (i) sudden changes in load demand in a microgrid.

A. Severe three-phase fault

A severe three-phase fault is applied at 1 s at the interconnection between microgrids 1 and 3. Fig. 6 shows the frequency response in microgrid 3 (solid line). In this case, the active power flow between microgrid 1 and 3 is shown in Fig. 7. It is clear from the figures that the proposed controller ensures stable operation during severe transients and the post-fault condition. Each STATCOM/ESS controller autonomously and effectively responds to the changes in system configurations and stabilizes it within a second without any steady-state error.

B. Superiority to unknown load dynamics

In this case study, an extra load with unknown dynamics is connected in microgrid 3. As the voltage will reduce due to the increase in the load the controller will act quickly to increase the reactive power supply. The STATCOM/ESS will provide extra active power and interconnection inverter will supply the

Fig. 8. Reactive power output of STATCOM/ESS in microgrid 1.

Fig. 9. Power flow from microgrid 2 to microgrid 3.

extra reactive power to balance the load. Fig. 8 shows the reactive power output of the STATCOM/ESS in microgrid 1. From Fig. 8, it is clear that other microgrids cooperate and share the power flow effectively to stabilize the voltage due to the increases in loads in microgrid 1. The frequency response in microgrid 3 due to the changes in loads is also shown in Fig. 6 (dotted line) and Fig. 9 shows the power flow from microgrid 2 to microgrid 3. From Fig 9 it is found that the designed controller provides excellent performance in terms of damping and settling time.

VI. CONCLUSIONS

In this paper a systematic procedure for designing distributed controllers is presented in order to regulate power flow among multiple islanded microgrids. The proposed controller utilizes a distributed H_2 control strategy and the appropriate inclusion of disturbances in the design process enhances the performance of the controller by minimizing dynamic interactions. The designed controller guarantees stability in the post-fault and the power balance of the system under extreme operating conditions. It provides feasible and smooth operation of coupled microgrids and load sharing among them. The simulation studies validate the desired performance of the microgrid subject to severe three-phase fault and sudden load variations which proves the efficacy and superiority of the designed controller. The future aim of this work is to design the controller considering the dynamics of nonlinear and voltage sensitive loads.

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