Droop Control for Islanded Microgrids with Compensating Approach

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Abstract—This paper proposes a droop control algorithm to distribute load changes automatically between two inverter-sourced generators in an islanded microgrid. A compensating approach is added to the conventional droop control scheme in order to add a power offset to the active power so that the output powers of the inverters remain balanced if the output of renewable energy varies. The droop control parameters are chosen based on eigenvalue analysis obtained from linear modal analysis. In this paper, it is shown that the proposed control method ensures effective power sharing and provides good performance under diverse operating conditions without the need for communication.

Index Terms—renewable energy source, voltage-source converter (VSC), microgrid, droop control, compensating approach, real power sharing, reactive power sharing.

I. INTRODUCTION

This paper focuses on an accurate decentralized droop control algorithm that can compensate the effect of the variation of renewable energy sources (RES)-based inverter input and share both active and reactive powers effectively when the renewable energy output varies and the load changes.

Presently fossil fuels are the main source of energy in different countries including Australia. Some environmental and economical concerns are caused by their use [1]. Renewable energy sources provide a better solution that can be installed as distributed-generation (DG) units [2] and offer many advantages such as environmental friendly operation, reduction of transmission and distribution losses and costs, higher energy efficiency and other economic benefits [3]. The operation and planning of the electrical network can be affected by the growing share of DG units [4]. This suggests a coordinated approach to integrate DG units, resulting in the concept of microgrid [5].

A microgrid consists of distributed energy system, such as loads and resources [6], [7]. It is also a controllable system, which is the key advantage in case of power networks [8]. In most cases, resources are connected to microgrid via voltage source converters, such as inverters, and microgrid is connected to the load-side at the point of common coupling (PCC) [9]. Microgrids do not have the rotating inertia [9]

and aggregated loads like conventional grids [10]. For stable operation of microgrids, various control approaches are used with or without communication [11], [12].

In recent years, different controllers for microgrids have been used. One of the schemes is droop-based control; in which controllers operate in an automatic process and provide reliable operation [13]. Conventional droop control consists of active power/frequency (P/f) control and reactive power/voltage (Q/V) control [14], that means active power sharing is based on frequency droop control [15]. Modern inverters are able to change the phase of the output rapidly and specifying the active power sharing control as a rate-of-change of angle droop control is more meaningful [16].

Most droop controllers are designed and implemented for VSC-connected microgrid by assuming instantaneous change in the output of the renewable energy source as the output requirements change. In reality, there is a delay before the output can change and during that interval a buffer, such as a capacitor, supplies or absorbs the difference in the inverter output power and the generated power. If it fails to buffer the mismatch adequately, a feedback controller can be utilized. In [17], an interesting control scheme has been proposed, although its implementation in effective load sharing has not been clarified. It also claims that the dc gain of the compensator, used for balancing the output power of the microgrid, should be unity but this does not result in sharing the RES power proportionally. The value of dc gain depends on the microgrid structure.

Since microgrids do not support the conventional method of reactive power sharing according to the generator terminal voltage [18], a linear model in terms of only output voltage of inverters has been used in [16]. It needs extension to include the impact of the phase angle of output voltage of inverters on reactive power sharing. Both the issues are taken into consideration in this paper.

The organization of the paper is as follows: Section II discusses the modeling of VSC-connected microgrid; system structure with the proposed control strategy and linearization are provided in Section III; Section IV contains the design steps for the proposed controller; controller performance is

evaluated in Section V and concluding remarks are outlined in Section VI.

II. MICROGRID MODELING

The basics of microgrid operations and research problems can be analyzed with the help of a two-source microgrid. Voltage source with controllable voltage magnitude and phase represents inverter-connected renewable energy generation [19]. The block diagram of two inverter-interfaced voltage-source microgrid with one load has been illustrated in Fig. 1. In this figure, P_{dc1} and P_{dc2} are the power outputs of two renewable energy sources. dc-link capacitors are used as buffer between generators and inverters. The VSC blocks convert dc voltages into ac. The inverters are fast and there are no stator transients. The voltage-sources are represented by $V_1 \angle \delta_1$ and $V_2 \angle \delta_1$ respectively.

Fig. 1: Block Diagram of a Simple Islanded Microgrid

III. SYSTEM STRUCTURE WITH CONTROL

This section contains the single line diagram, as seen in Fig. 2, of the considered non-linear microgrid system with linearization and control.

Fig. 2: Single Line Diagram of a Simple Islanded Microgrid

The currents and bus voltages in the microgrid are related as:

$$Y_{bus} V_{bus} = I_{bus} \quad (1)$$

$$Y_{bus} = \begin{bmatrix} \frac{1}{Z_{13}} & 0 & -\frac{1}{Z_{13}} \\ 0 & \frac{1}{Z_{23}} & -\frac{1}{Z_{23}} \\ -\frac{1}{Z_{13}} & -\frac{1}{Z_{23}} & \frac{1}{Z_{13}} + \frac{1}{Z_{23}} + \frac{1}{Z_L} \end{bmatrix} \quad (2)$$

$$V_{bus} = \begin{bmatrix} V_1 \angle \delta_1 \\ V_2 \angle \delta_2 \\ V_3 \angle \delta_3 \end{bmatrix}; I_{bus} = \begin{bmatrix} I_1 \angle \theta_1 \\ I_2 \angle \theta_2 \\ I_3 \angle \theta_3 \end{bmatrix} \quad (3)$$

A. System Parameters

The transmission line parameters are $Z_{13} = j0.25$ pu and $Z_{23} = j0.05$ pu.

B. Load-flow Analysis

Load-flow analysis is used to determine the initial set values of different bus parameters. It is assumed that bus-1 is a generator bus, bus-2 is a slack or reference bus and bus-3 is a load bus. Considered initial set values: $P_1^0 = 0.5$ pu, $V_1^0 = 1$ pu, $V_2^0 = 1$ pu, $\delta_2^0 = 0^0$ and load resistor, $Z_L = 1$ pu. Load-flow solution gives the initial set values of δ_1, V_3 , and δ_3 ; these are: $\delta_1^0 = 5.7663^0$, $V_3^0 = 0.9984$ pu, $\delta_3^0 = -1.4258^0$. Using (1), $I_1^0 = 0.5014$ pu, $\theta_1^0 = 1.4544^0$, $I_2^0 = 0.4983$ pu, $\theta_2^0 = -4.3241^0$, $P_2^0 = 0.4969$ pu, $P_3^0 = P_{Z_L}^0 = 0.9969$ pu, $Q_1^0 = 0.0377$ pu, $Q_2^0 = 0.0376$ pu.

C. Proposed Control Strategy

In this sub-section, the background of droop control and its modification for the purpose of sharing the load in a desired manner are described. The active and reactive powers are expressed by the following equations [20]:

$$S_{12} = P_{12} + jQ_{12} \quad (4)$$

$$P_{12} = \frac{V_1}{R_{12}^2 + X_{12}^2} [R_{12}V_1 - R_{12}V_2 \cos(\delta_1 - \delta_2) + X_{12}V_2 \sin(\delta_1 - \delta_2)] \quad (5)$$

$$Q_{12} = \frac{V_1}{R_{12}^2 + X_{12}^2} [X_{12}V_1 - X_{12}V_2 \cos(\delta_1 - \delta_2) - R_{12}V_2 \sin(\delta_1 - \delta_2)] \quad (6)$$

For overhead transmission lines, reactance is greater than resistance, i.e., $X_{12} \gg R_{12}$. Consequently, R_{12} may be neglected. If the difference between power angles, $\delta_1 - \delta_2$ is small, $\sin(\delta_1 - \delta_2) = \delta_1 - \delta_2 = \Delta\delta$ and $\cos(\delta_1 - \delta_2) = 1$. (4) and (5) then become,

$$\Delta\delta = \frac{X_{12}P_{12}}{V_1V_2} \quad (7)$$

$$V_1 - V_2 = \Delta V = \frac{X_{12}Q_{12}}{V_1} \quad (8)$$

Based on these relations, the droop equations are [21] ($i = 1, 2$):

$$\Delta\delta_i = -k_{p_i}(P_{m_i} - P_i^0) \quad (9)$$

$$\Delta V_i = -k_{q_i}(Q_{m_i} - Q_i^0) \quad (10)$$

where, subscript m stands for measured values.

This paper modifies the traditional droop control strategy, known as droop control, with compensation. This is because of ascertaining the balance in the output active power of the microgrid by changing it according to the change in the dc bus voltage of the power sources, V_{dc_i} . For this purpose power offset, which is added to the output active power, is expressed as a function of the variation of dc-link voltage [17]. The proposed droop equations ($i = 1, 2$):

$$P_{ft_i}^0 = k_{dc_i}(V_{dc}^0 - V_{dc_i}) + k_i \int (V_{dc}^0 - V_{dc_i}) dt \quad (11)$$

where, $P_{ft_i}^0$ is the offset power. Proportional control controls $(V_{dc}^0 - V_{dc_i})$ to a constant, while integral control keeps it

equal to a pre-defined value. In this paper, $k_i = 0$.

$$\Delta \dot{\delta}_i = -k_{p_i}(P_{m_i} + P_{f_{t_i}}^0 - P_i^0); \Delta V_i = -k_{q_i}(Q_{m_i} - Q_i^0) \quad (12)$$

where, $w_f = 12 \text{ rad s}^{-1}$, $k_{p_1} = 1.2$, $k_{p_2} = 6$, $k_{q_1} = 0.0012$ and $k_{q_2} = 0.006$. These parameters are chosen in accordance with the eigenvalue analysis of the linearized closed-loop system being presented in the next sub-section.

Let assume real and reactive power measurement sensors have a first-order dynamics and their transfer functions [16] ($i = 1, 2$):

$$\frac{P_{m_i}(s)}{P_i(s)} = \frac{w_f}{s + w_f}; \quad \frac{Q_{m_i}(s)}{Q_i(s)} = \frac{w_f}{s + w_f} \quad (13)$$

In Fig. 3, the proposed droop controller controls voltage and phase angle of dc/ac converter-connected voltage-source, which is connected in an islanded microgrid, when either renewable generation, load or both vary. For example, if load changes, the variation between original load and measured load change is multiplied by droop gains and the controller controls it in a way that angle difference, voltages, real powers and reactive powers of the system remain stable. Same process is done for dc bus voltage variation. The droop control equations are denoted in this diagram by means of summations and gains.

Fig. 3: The Proposed Droop Control Scheme

D. Linear Modal Analysis

Linear modal analysis of the non-linear inductive microgrid with the controller is carried out in this paper to tune control parameters and to attain a better understanding of the dynamics of the microgrids. The complex power can be written as ($i, j = 1, 2; j \neq i$):

$$S_i = P_i + jQ_i = V_i \angle \delta_i \times I_i \angle -\theta_i \quad (14)$$

$$I_i \angle -\theta_i = \sum_{j=1}^2 Y_{reduced_{ij}} V_j \angle \delta_j \quad (15)$$

$$Y_{reduced_{ij}} = Y_{ij} - Y_{i2} Y_{22}^{-1} Y_{2j} \quad (16)$$

Two voltage-sources and the load bus are grouped in '1' and '2' respectively to make Y_{ij} from Y_{bus} and if it is considered

that $Y_{reduced_{ij}} = G_{ij} + jB_{ij}$, $\delta_{ij} = \delta_i - \delta_j$, then putting (14) and (15) together [16]:

$$P_i = \sum_{j=1}^2 V_i V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \quad (17)$$

$$Q_i = \sum_{j=1}^2 V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \quad (18)$$

The Taylor series expansion for P_i and Q_i can be written as ($i = 1, 2; j \neq i$):

$$\begin{aligned} P_i &= P_i^0 + \Delta P_i \\ &= P_i^0 + \sum_{j=1}^2 V_j^0 (G_{ij} \cos \delta_{ij}^0 + B_{ij} \sin \delta_{ij}^0) \Delta V_i \\ &\quad + \sum_{j=1}^2 V_i^0 (G_{ij} \cos \delta_{ij}^0 + B_{ij} \sin \delta_{ij}^0) \Delta V_j \\ &\quad + \sum_{j=1}^2 V_i^0 V_j^0 (-G_{ij} \sin \delta_{ij}^0 + B_{ij} \cos \delta_{ij}^0) \Delta \delta_{ij} \end{aligned} \quad (19)$$

$$\begin{aligned} Q_i &= Q_i^0 + \Delta Q_i \\ &= Q_i^0 + \sum_{j=1}^2 V_j^0 (G_{ij} \sin \delta_{ij}^0 - B_{ij} \cos \delta_{ij}^0) \Delta V_i \\ &\quad + \sum_{j=1}^2 V_i^0 (G_{ij} \sin \delta_{ij}^0 - B_{ij} \cos \delta_{ij}^0) \Delta V_j \\ &\quad + \sum_{j=1}^2 V_i^0 V_j^0 (G_{ij} \cos \delta_{ij}^0 + B_{ij} \sin \delta_{ij}^0) \Delta \delta_{ij} \end{aligned} \quad (20)$$

where, $\Delta \delta_{ij} = \Delta \delta_i - \Delta \delta_j$ and $\Delta \delta_i = \delta_i - \delta_i^0$. Let define $\Delta P_{m_i} = P_{m_i} + P_{f_{t_i}}^0 - P_i^0$ and $\Delta Q_{m_i} = Q_{m_i} - Q_i^0$. The system described by (12) and (13) can now be linearly represented as:

$$\Delta \dot{\delta}_1 = -k_{p_1} \Delta P_{m_1} \quad (21)$$

$$\Delta \dot{\delta}_2 = -k_{p_2} \Delta P_{m_2} \quad (22)$$

$$\begin{aligned} \Delta \dot{P}_{m_1} &= -w_f (\Delta P_{m_1} - \Delta P_1) \\ &= -w_f \Delta P_{m_1} + w_f \Delta P_{1\delta_1}^0 \Delta \delta_1 + w_f \Delta P_{1\delta_2}^0 \Delta \delta_2 \\ &\quad + w_f \Delta P_{1V_1}^0 \Delta V_1 + w_f \Delta P_{1V_2}^0 \Delta V_2 \end{aligned} \quad (23)$$

$$\begin{aligned} \Delta \dot{P}_{m_2} &= -w_f (\Delta P_{m_2} - \Delta P_2) \\ &= -w_f \Delta P_{m_2} + w_f \Delta P_{2\delta_1}^0 \Delta \delta_1 + w_f \Delta P_{2\delta_2}^0 \Delta \delta_2 \\ &\quad + w_f \Delta P_{2V_1}^0 \Delta V_1 + w_f \Delta P_{2V_2}^0 \Delta V_2 \end{aligned} \quad (24)$$

$$\begin{aligned} \Delta \dot{Q}_{m_1} &= -w_f (\Delta Q_{m_1} - \Delta Q_1) \\ &= -w_f \Delta Q_{m_1} + w_f \Delta Q_{1\delta_1}^0 \Delta \delta_1 + w_f \Delta Q_{1\delta_2}^0 \Delta \delta_2 \\ &\quad + w_f \Delta Q_{1V_1}^0 \Delta V_1 + w_f \Delta Q_{1V_2}^0 \Delta V_2 \end{aligned} \quad (25)$$

$$\begin{aligned} \Delta \dot{Q}_{m_2} &= -w_f (\Delta Q_{m_2} - \Delta Q_2) \\ &= -w_f \Delta Q_{m_2} + w_f \Delta Q_{2\delta_1}^0 \Delta \delta_1 + w_f \Delta Q_{2\delta_2}^0 \Delta \delta_2 \\ &\quad + w_f \Delta Q_{2V_1}^0 \Delta V_1 + w_f \Delta Q_{2V_2}^0 \Delta V_2 \end{aligned} \quad (26)$$

where, the constants $\Delta P_{i\delta_j}^0$, $\Delta P_{iV_j}^0$, $\Delta Q_{i\delta_j}^0$ and $\Delta Q_{iV_j}^0$ can be obtained from (19) and (20). The eigenvalues of the

linearized system at the equilibrium point after the change in renewable generation and load impedance are : -12, -12, -12, 0, -6+j15.3921 and -6-j15.3921. It has been found that the system behavior, shown in Figs. 4-9, is captured by eigenvalues.

IV. DESIGN STEPS OF THE PROPOSED CONTROLLER

The controller proposed in this paper is designed in two steps:

- (i) Droop gains (k_{p1} , k_{p2} , k_{q1} and k_{q2}) are selected according to the eigenvalue analysis of inductive microgrid structure such that the system is damped;
- (ii) Dc gains (k_{dc1} and k_{dc2}) are also chosen based on the same criteria of eigenvalues of the closed-loop system mentioned in the previous step but its value should be such that proportional power sharing is possible.

V. CONTROLLER PERFORMANCE EVALUATION

The performance of the designed controller is evaluated in this section by means of stability analysis and load sharing performance so that its feasibility during both dc bus voltage and load impedance variations can be highlighted. Two VSC-connected generators and one load are considered in the test system as shown in Fig. 2.

A. Sudden Change in Renewable Generation

Let assume a situation where a sudden change occurs in the generated power of the dc micro sources at 0 second. P_{dc_i} and V_{dc_i} change from their set values. Now, the proposed feedback control strategy changes the output powers of microgrid in accordance with the change of V_{dc_i} with a view to obtaining a natural balancing.

Fig. 4: Angle Difference during Variable Renewable Generation

When there is a sudden reduction, say 10 percent, in dc generation at 0 second transients are found both in the microgrid power and angle difference. The proposed control returns the system to a steady-state within 1.1 seconds that can

be noticed from Fig. 4 and Fig. 5, indicating stable operation after transients. The dc gains, k_{dc_i} , are selected for a given operating condition. In this case they are 0.0001.

Fig. 5: Real Powers during Variable Renewable Generation

B. Change in Renewable Generation and Load Impedance

In this sub-section, the proposed control methodology is applied when load impedance change takes place, i.e., Z_L changes from 1 pu to $0.5+j0.25$ pu, along with 10 percent increase in renewable generation.

The voltage magnitudes and angles, real and reactive powers with the proposed droop controller are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9 respectively. It is seen from Fig. 6 that the difference between the angles of the considered microgrid approaches a constant value of 11.7945° , thus ensuring a stable operation.

The system is almost damped with slight initial oscillations because of real and reactive measurement sensor dynamics.

Fig. 6: Angle Difference during Variable Renewable Generation and Load Impedance

Fig. 7: Real Powers during Variable Renewable Generation and Load Impedance

Fig. 8: Voltages during Variable Renewable Generation and Load Impedance

Fig. 9: Reactive Powers during Variable Renewable Generation and Load Impedance

C. Real Power Sharing

It is necessary that the real and reactive power are such that $\dot{\delta}_1 = \dot{\delta}_2$ for stable operation of the system.

Define $\Delta P_i = P_{mi} + P_{ft_i}^0 - P_i^0$, where $i = 1, 2$; and from the first part of (12),

$$\Delta P_1 = \frac{k_{p2}}{k_{p1}} \Delta P_2 = 5 \Delta P_2 \quad [k_{p1} = 1.2, k_{p2} = 6] \quad (27)$$

The steady-state values of real power of both the inverter-connected voltage-sources are $P_1=0.8971$ pu and $P_2=0.5759$ pu. Now, $\Delta P_1=P_1-P_1^0=0.3971$ pu and $\Delta P_2=P_2-P_2^0=0.079$ pu, giving $\Delta P_1 \cong 5 \Delta P_2$, which indicates that the control analysis resembles the stability criteria and load is shared at a ratio of 5:1.

D. Reactive Power Sharing

The linear model of the system is further analyzed with the second part of (12) in order to share reactive power. In this case Y_{bus} matrix is not reduced and $Y_{ij} = G_{ij} + jB_{ij}$. The reactive power flow of three-bus system ($i = 1, 2, 3$):

$$Q_i = \sum_{j=1}^3 V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \quad (28)$$

For negligible G_{ij} , it can be written [16],

$$Q_1 = -V_1 V_3 B_{13} \cos \delta_{13} - V_1^2 B_{11} \quad (29)$$

$$Q_2 = -V_2 V_3 B_{23} \cos \delta_{23} - V_2^2 B_{22} \quad (30)$$

$$Q_3 = -V_3 V_1 B_{31} \cos \delta_{31} - V_3 V_2 B_{32} \cos \delta_{32} - V_3^2 B_{33} \quad (31)$$

Let there be a change in the reactive power at node-3 of Fig. 1 and using (10), it can be written as:

$$\Delta Q_1 = k_{q1} \Delta Q_1 V_3^0 B_{13} \cos \delta_{13}^0 - V_1^0 |\Delta V_3| B_{13} \cos \delta_{13}^0 + V_1^0 V_3^0 B_{13} \sin \delta_{13}^0 + 2k_{q1} \Delta Q_1 V_1^0 B_{11} \quad (32)$$

$$\Delta Q_2 = k_{q2} \Delta Q_2 V_3^0 B_{23} \cos \delta_{23}^0 - V_2^0 |\Delta V_3| B_{23} \cos \delta_{23}^0 + V_2^0 V_3^0 B_{23} \sin \delta_{23}^0 + 2k_{q2} \Delta Q_2 V_2^0 B_{22} \quad (33)$$

$$\Delta Q_3 = k_{q1} \Delta Q_1 V_3^0 B_{31} \cos \delta_{31}^0 - V_1^0 |\Delta V_3| B_{31} \cos \delta_{31}^0 + V_1^0 V_3^0 B_{31} \sin \delta_{31}^0 + k_{q2} \Delta Q_2 V_3^0 B_{32} \cos \delta_{32}^0 - V_2^0 |\Delta V_3| B_{32} \cos \delta_{32}^0 + V_2^0 V_3^0 B_{32} \sin \delta_{32}^0 - 2|\Delta V_3| V_3^0 B_{33} \quad (34)$$

where, $|\Delta V_3| = V_3^0 \sqrt{(\cos \delta_3)^2 + (-\sin \delta_3)^2} = V_3^0$

The simplified forms of (31) and (32) are,

$$\Delta Q_1 = \frac{-V_1^0 |\Delta V_3| B_{13} \cos \delta_{13}^0 + V_1^0 V_3^0 B_{13} \sin \delta_{13}^0}{1 - k_{q1} V_3^0 B_{13} \cos \delta_{13}^0 - 2k_{q1} V_1^0 B_{11}} \quad (35)$$

$$\Delta Q_2 = \frac{-V_2^0 |\Delta V_3| B_{23} \cos \delta_{23}^0 + V_2^0 V_3^0 B_{23} \sin \delta_{23}^0}{1 - k_{q2} V_3^0 B_{13} \cos \delta_{23}^0 - 2k_{q2} V_2^0 B_{22}} \quad (36)$$

It is clearly found from (35) and (36) that the ratio of change in ΔQ_1 and ΔQ_2 , due to change in ΔQ_3 , using the proposed droop strategy gives the reactive power sharing ratio.

VI. CONCLUSION

In this paper a decentralized droop control, with the addition of a compensator, has been proposed to enhance the feasibility of the conventional droop control scheme. A systematic procedure of implementing the proposed controller for a variable dc generation and load-based VSC-connected islanded inductive microgrid has been outlined. The designed controller guarantees system stability in both cases. Simulated results suggest that this control approach is effective enough to share active power based on droop parameters that are required for active power sharing. This paper also includes an analysis based on the linear model that makes it easier to understand reactive power sharing in microgrids depending on the reactive power droops and other microgrid system parameters. Further improvements can be made by extending the proposed controller design to include filtering approach in RES-based complex microgrids, consisting of multiple DG units and loads.

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