An Improved Droop Control Method to Enhance Dynamic Performance of AC Microgrid

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Abstract—The sources, interfaced with the microgrid using power electronic converters have inherently low physical inertia. With step variation in load demand, voltage and frequency difference are created among the sources during transient and the low frequency oscillations appear in the power supplied through the interconnecting lines. This may even lead to false triggering of fault protection system. To suppress these transient in powers and to improve dynamic response of microgrid in islanded mode, a modified droop controller which uses dynamic variation in droop gains of active power frequency ($P - \omega$) characteristics is proposed. The variation of droop gains is based on the rate of change of active power supplied by the corresponding source. Key advantages offered by the modified droop controller are improved dynamic response with reduced peaks in power supplied by the sources during step change in load power demand. The effectiveness of the proposed technique is demonstrated using linearized model derived for microgrid taking into account the dynamics of proposed controller, loads and distribution network. The root loci plots are used to study the behavior of the ac microgrid with respect to variation in parameters of proposed controller. The effectiveness of the controller is validated using simulation study in Simulink/Matlab for a microgrid test model.

Keywords—AC Microgrid, root loci plots, stability analysis, modified droop laws

I. INTRODUCTION

Microgrid includes various sources, loads and storage elements connected through Power Electronics Converters (PECs). It is desirable that power supplied by the sources and storage elements must be shared in proportion to their scheduled values as determined by Distribution System Operator (DSO) [1]. To ensure proportional power sharing without using communication among PECs, droop controllers are widely used [2]. Fig. 1 shows a generalized radial configuration of an ac microgrid with various sources and loads.

Accurate sharing of active power-frequency droop law is possible in ac microgrid using conventional active power droop law. However, due to mismatching in interconnecting cable or feeders impedances, accuracy in reactive power sharing becomes poor. Reactive power sharing error is minimized by using high value of reactive power droop gains [3], [4]. The low frequency modes (dominant eigenvalues) are most sensitive to droop gains. The relative stability of the system decreases with increase in droop gains which may even lead to unstable operation of microgrid. Due to reduction in stability margin, the damping of the system decreases and dynamic response of system becomes oscillatory [3]–[5]. Poor transient response leads to voltage/frequency difference between the sources during transient condition. The transient peaks appear in power supplied by the sources, which may lead to overloading and/or false triggering of the fault protection systems during the load transients [5], [6]. Therefore, a trade off exists between the power sharing accuracy and dynamic response of microgrid, when it is operating in islanded mode.

To enhance the stability margin of microgrid at high droop gains and to improve the dynamic response, modified droop laws are suggested in literature. In [6], additional terms corresponding to the derivative and integral components of active power and reactive power supplied by the sources are incorporated as opposed to conventional droop laws. Incorporation of these terms reduces oscillations in the output power of sources. Step variation in load demand may lead to shifting of dominant poles (corresponding to power sharing dynamics) towards the imaginary axis [7]. The response of the microgrid is improved by determining gains of the derivative/integral terms in an adaptive manner. In [7], the value of gains are determined based on the power supplied to the load by each source. The adaptive variation in coefficients of derivative terms decreases oscillations in output power with step variation in load power demands.

Use of conventional droop laws (between $P - \omega$ and $Q - E$) in low voltage microgrid (interconnecting cables or feeders have high value of resistance to inductance ratio), leads to reduction in stability margin and the response of the system becomes oscillatory due to coupling between $P$ and $Q$ [8], [9]. The coupling takes place due to increased dependence of $P$ and $Q$ on $E$ and $\omega$ respectively. Therefore, opposite droop laws, (between $P - E$ and $Q - \omega$) are used for accurate power sharing and to improve efficiency in low voltage microgrid [10]. However, these droop laws may lead to inaccurate sharing of active power due to unequal voltage drops across the feeders or interconnecting cables. In order to ensure decoupled active

Fig. 1. Generalized block diagram of ac microgrid
and reactive powers control with enhanced system stability, virtual $P - Q$ and $E - \omega$ frame based control methods are suggested in [11], [12]. With the help of these frames, the coupled active and reactive power are transformed to virtually decoupled active and reactive power. However, the method discussed in [11] requires the information of interconnecting line parameters.

To overcome these limitations, techniques based on emulation of virtual impedance at the output of inverter are suggested in [13], [14]. To ensure that active and reactive powers are virtually decoupled and to ensure stabilized operation of low voltage microgrid, virtual inductor is emulated at the output of source inverter [13]. To further improve the dynamic response, adaptive variation in virtual complex impedance parameters is suggested in [14]. However, the poor design and inaccurate implementation of virtual impedances may further affect the power quality, system stability and transient response of power sharing dynamics as discussed in [14].

In addition to droop gains, the stability of the microgrid is affected by the dynamics of distribution network and loads. The sensitivity of low frequency modes (dominant eigenvalues) is high to network topology [4]. The control techniques discussed in above mentioned references does not take into account the interaction dynamics between source and load/network, therefore it may result in poor dynamic performance and reduced stability margin in diversified networks having large number of source and loads. Authors in [15] modified the conventional droop control by shifting the nominal voltage level using the auxiliary signals. The proposed technique includes an identification algorithm required to calculate the parameters of auxiliary signals. Response of the system becomes slow if the speed of adaptation of identification algorithm is low. To overcome the limitation of adaption speed, a modified adaptive feed-forward control scheme is suggested in [16]. The technique calculates auxiliary signals using the average power available at the output of low pass filters. However, the power sharing dynamics becomes poor with decrease in the value of cut off frequency of low pass filter. To eliminate inherent delay caused due to low pass filter, a modified droop control scheme based on piece wise linear approximation of droop gain is suggested in [17]. The proposed droop controller adjusts inverter output voltage as function of current. The power sharing problem is thus realized in the form of current sharing problem as in the case of a dc microgrid. However, the power sharing accuracy is poor if there is a large mismatching in interconnecting line parameters.

To suppress the transient peaks in powers supplied by sources and to improve dynamic response of microgrid in islanded mode without affecting power sharing accuracy at steady state, technique using dynamic variation in droop gains of active power frequency ($P - \omega$) characteristics is proposed in this paper. The variation in droop gain depend on the rate of change of active power supplied by the sources. The proposed controller causes shifting of low frequency dominant modes (dominant complex eigenvalues) towards the real axis of LHP (Left Hand Plane). The oscillations in the power supplied by sources during step change in load power demand are reduced. At steady state, the modified droop controller is reduced to conventional one, therefore the steady state response of the system remains unaffected. The effectiveness of proposed controller is demonstrated with help of linearized mathematical model derived for ac microgrid taking into the dynamics of proposed controller, loads and distribution network. The validation for improved performance of the system with the controller is carried out using simulation studies for a microgrid test model based on IEEE-14 bus system [18].

The organization of the paper is as follows: Section II discusses the proposed controller used for improvement of the dynamic performance of system. In section III, small signal model of the microgrid with modified droop law, is derived. Further, eigenvalue loci plots are used to reflect the sensitivities of eigenvalues on system parameters. Simulation studies are included in section IV. Section V includes the conclusions of the present work.

II. PROPOSED DROOP CONTROLLER FOR IMPROVED DYNAMIC RESPONSE

![Fig. 2. Effect of proposed controller on slope of (a) $P - \omega$ characteristics (b) $Q - E$ droop characteristics](image)

The droop control laws are employed to control the active and reactive power supplied by sources in proportion to their rated capacity in ac microgrid without requiring communication among the sources. The modified dynamic droop laws used to reduce oscillations in the output active power $p_{fi}$ and reactive power $q_{fi}$ supplied by the $i^{th}$ source are given by,

\[
\omega_i = \omega_{oi} - k_{pi} p_{fi}
\]

\[
e_i = E_{oi} - k_{qi} q_{fi}
\]

where, $\omega_i$, $\omega_{oi}$, $e_i$ and $E_{oi}$ are the instantaneous, nominal value of frequency, reference and nominal voltages of $i^{th}$ source. The elements $p_{fi}$ and $q_{fi}$ are the filtered values of average active and reactive power. The elements $k_{pi}$ and $k_{qi}$ are the slopes of $P - \omega$ and $Q - E$ characteristics which are dynamic droop gains determined by,

\[
k_{pi} = k_{pi0} + g_{pi} \frac{dp_{fi}}{dt}
\]

\[
k_{qi} = k_{qi0} + g_{qi} \frac{dq_{fi}}{dt}
\]

The coefficients $g_{pi}$ and $g_{qi}$ are constants and their values are selected to ensure stability and improved dynamic response. As the inertia of power electronic based source is small, therefore, the frequency and voltage difference is created among different sources during the step change in load power demand. The value of frequency and voltage deviations will be maximum for the sources connected near to the load under going step variation in load demand. To minimize these frequency and voltage deviations, the sources having maximum frequency and
voltage deviations will supply more power as compared to the remote sources. Hence more oscillations will appear in active and reactive power which are supplied by the nearby source in transient condition as compared to remote sources. The non-zero values of $dp_{fi}/dt$ and $dq_{fi}/dt$, modify instantaneous values of dynamic droop gains $k_{pi}^*$ and $k_{qi}^*$. The effective value of droop gains $k_{pi}^*$, $k_{qi}^*$ will be more for the nearby source as compared to remote sources. Therefore, the corresponding source will supply less power and rest of the power will be shared by the remaining sources during transient state. These modified values of $k_{pi}^*$ and $k_{qi}^*$ reduce the peak overshoot in active and reactive power and improve transient response of microgrid. When output power supplied by the source settles at its new steady state value, the droop laws are reduced to normal droop laws. Effects of proposed controller on $P - \omega$ and $Q - E$ characteristics are shown in Fig. 2a and 2b.

### III. MODELING OF THE PROPOSED CONTROLLER

Fig. 2 shows a generalized radial network of ac microgrid with various sources and loads connected to ac bus. The sources and dc loads are interfaced to the ac microgrid through power electronic converters, while ac loads are directly connected. A three phase Voltage Source Inverter (VSI) is used to connect these sources to the ac microgrid and includes inner and outer controller as shown in Fig. 3. The inner loops include current and voltage controllers, used for generating the sinusoidal output of reference magnitude and frequency. These controllers are implemented in $d-q$ reference frame rotating at a speed generated by $P - \omega$ droop controller. The outer controller is the proposed droop controller which generate reference values corresponding to magnitude and frequency of output voltage of source. It is assumed that the dynamics of inner loops are faster than the droop controllers. A linearized reduced order model is used for analysis neglecting faster dynamics of inner voltage and current control loops.

The modified droop laws are derived by substituting $k_{pi}^*$ from (3) to (1) and $k_{qi}^*$ from (4) to (2),

$$\omega_i = \omega_{oi} - (k_{pi} + g_{pi}\frac{dp_{fi}}{dt})p_{fi} \quad (5)$$

$$e_i = E_{oi} - (k_{qi} + g_{qi}\frac{dq_{fi}}{dt})q_{fi} \quad (6)$$

The droop laws in (5) and (6) improve the transient response of the system by modifying the instantaneous values of $k_{pi}$ and $k_{qi}$. The change in the values of $k_{pi}^*$ and $k_{qi}^*$ depend upon the values of coefficients $g_{pi}$ and $g_{qi}$, and derivative of $p_{fi}$ and $q_{fi}$ with respect to time.

Average values of real power $p_i$ and reactive power $q_i$ supplied by $i^{th}$ source, are given by $p_i = e_{di}i_{di} + e_{qi}i_{qi}$ and $q_i = e_{di}i_{qi} - e_{qi}i_{di}$, where, $e_{di}$, $i_{di}$, and $e_{qi}$, $i_{qi}$ are the d-axis and q-axis components of three phase output voltage and current supplied by the source respectively. With low pass filter, the filtered values of active $p_{fi}$ and reactive power $q_{fi}$ are expressed as,

$$p_{fi} = -\omega_c p_i + \omega_c p_i \quad (7)$$

$$q_{fi} = -\omega_c q_i + \omega_c q_i \quad (8)$$

In (7) and (8), $\omega_c$ is the low pass filter’s cut-off frequency.

Sources $i$ and $j$ are connected through interconnecting cable having resistance $R_{bij}$ and inductance $L_{bij}$, respectively. By Kirchhoff’s Voltage Law (KVL), the branch current $i_{bij}$ and branch voltage $e_{bij}$ are related by following relation,

$$L_{bij}\frac{di_{bij}}{dt} + R_{bij}i_{bij} = e_{bij} = e_i - e_j \quad (9)$$

At each bus, a simple $R - L$ load is connected. The dynamical relation for current drawn by the load connected at $i^{th}$ bus is given by,

$$L_{li}\frac{di_i}{dt} + R_{li}i_i = e_i \quad (10)$$

where, $L_{li}$ and $R_{li}$ are the inductance and resistance of $i^{th}$ load.

By applying Kirchhoff’s current law, at each bus of test model shown in Fig. 4,

$$i_s - i_l = M_{lb} \quad (11)$$

where, $i_s$, $i_l$ and $i_b$ are source current vector, load current vector and branch current vector. The element $M$ is the incidence matrix of the test model shown in Fig. 4. The dimensions of $M$ is $n \times m$, with $n$ number of buses and $m$ as number of branches. Output voltage produced by $i^{th}$ source is $e_i$, aligned at an angle $\delta$, with d-axis of synchronously rotating $d-q$ reference frame. Referring to the small signal analysis, the linearized relations for $\Delta \dot{x}$, $\Delta p_{fi}$, $\Delta q_{fi}$, $\Delta e_i$ and $\Delta q_{ij}$ components of $i_b$ and $i_i$ in matrix form using (5-11) for the microgrid shown in Fig. 4, are derived. The detailed modeling of various elements of ac microgrid is discussed in [19]. These equations are converted into the standard state space form, which is \( \Delta \dot{x} = A \Delta x + B \Delta u \). Generalized state space model of microgrid is obtained as,

$$\Delta x_{mg} = A_{mg} \Delta x_{mg} + B_{mg} \Delta u \quad (12)$$

where, $\Delta x_{mg}$ represents the column matrix of state variables, $A_{mg}$ is the state matrix and $B_{mg}$ is the input matrix. The equations represents small signal dynamics of the system shown in Fig. 4. The values of these matrices are given by,

$$A_{mg} = \begin{bmatrix} R^{-1}A \end{bmatrix}, \quad B_{mg} = \begin{bmatrix} R^{-1}B \end{bmatrix} \quad (13)$$

$$x_{mg} = \begin{bmatrix} \Delta \delta \Delta p_f \Delta q_f \Delta i_{ld} \Delta i_{iq} \Delta i_{ld} \Delta i_{iq} \end{bmatrix} \quad (14)$$

The values of matrices $R$, $A$ and $B$ are given by,
The parameters of the test model considered for analysis are given in Table I.

### A. Effect of Control Gains $g_p$ and $g_q$ on Stability of Microgrid

The root loci plots are determined using the system matrix $A_{mg}$ given in (12). The gains $g_p$ and $g_q$ associated with non-linear terms in droop control laws are responsible for governing the transient response of the microgrid. In this section, the effect of gains $g_p$ and $g_q$ on the transient performance of microgrid is observed using root loci plots which are presented in Fig. 5. These plots help in the selection of values of gains $g_p$ and $g_q$ to achieve reduction in oscillation in power supplied by the sources during transient condition.

#### 1) Effect of Gain $g_p$ on Stability of Microgrid

The root loci plot for increasing values of $g_p$ is shown in Fig. 5a. For increasing values of gain $g_p$, the eigenvalues shift towards the real axis indicated by eigenvalues loci. For $g_{p1} = g_{p2} = g_{p3} = g_{p6} = g_{p8} = 1 \times 10^{-6}$ rad/watt$^2$, all eigenvalues are located on the negative real axis of s-plane. On further increment in $g_p$ of all sources, the root loci plots break away and eigenvalues start shifting towards the imaginary axis for higher values of $g_{p1}$. Hence, from these plots, it is concluded that microgrid operation becomes more damped for increasing values of $g_p$, and for very high values of $g_p$ ($g_p = 1000g_p$), the microgrid operation becomes unstable. Therefore, for better dynamic performance, the value of $g_p$ for which maximum number of eigenvalues settle near to real axis, is selected. For $g_{p1} = g_{p2} = g_{p3} = g_{p6} = g_{p8} = 1.4 \times 10^{-6}$ rad/watt$^2$, it is observed that there is no observable movement of eigenvalues towards the imaginary axis for increasing values of $k_p$. The power sharing dynamics becomes insensitive to the active power droop gain of sources, which enables the operation of the microgrid at higher values of active power droop gains.

#### 2) Effect of Gain $g_q$ on Stability of Microgrid

The Fig. 5b shows the roots loci plot of eigenvalues for increasing values of gain $g_q$. For increasing values of gain $g_q$, dominant eigenvalues shift towards the imaginary axis and other move away from the real axis. This indicates that the response of the system becomes oscillatory for increasing values of $g_q$. For large values of $g_q$, the eigenvalues shift into Right Hand Plane (RHP) causing operation of microgrid to be unstable.

From the eigenvalues root loci plots shown in Figs. 5a and 5b, it is concluded that when $g_p$ increases, both the stability margin and damping of system improves. However, the damping reduces with increasing values of $g_q$. This indicates that using the modified droop law in $Q - E$ leads to deteriorated dynamic performance of the system. Therefore,
for realizing stabilized operation of microgrid with improved dynamic response, the modified droop law between frequency and active power should be used rather than modified droop law between reactive power and voltage. The value of gain $g_p$ for which low frequency modes are more damped should be selected. Similar trends in eigenvalue loci plots are observed for the ac microgrid having three sources connected in the form of ring network.

B. Comparison of Modified Droop Controller with Conventional Droop Law

To show the effectiveness of the modified droop controller, microgrid test model based on IEEE-14 bus system is simulated in Matlab/Simulink. It consists of 5 sources static in nature, 11 loads and 14 buses. The single line diagram of the microgrid test model is shown in Fig. 4. and parameters of the complete system are given in Table 1. Sources are connected at buses 1, 2, 3, 6 and 8. The rating of each source is 10 MVA. The loads are connected at buses 2, 3, 4, 5, 6, 9, 10, 11, 12, 13 and 14. A balanced three phase load is connected at each load bus. The microgrid test model shown in Fig 4 is assumed to be energized by all sources at $t = 0$.

1) Performance of Conventional Droop Law: To validate the modified droop controller, the microgrid test model shown in Fig. 4, is simulated using Simulink. The results generated using simulation study are included in this section. Performance of the microgrid is evaluated under different loading conditions. Each source is a three phase VSI. Initially the active and reactive power load demands at bus 2, 3, 4, 5 and 6 are 4 MW and 2 MVAr, while at bus 9, 10, 11, 12, 13 and 14, these are 2 MW and 1 MVAr. Now at time instant $t = 1.5$ s, a step change in load demand from 4 MW/2 MVAr to 8 MW/6 MVAr at bus 3, from 4 MW/2 MVAr to 6 MW/4 MVAr at bus 4 and 5 is provided. Again at $t = 2.5$ s, the load demand is switched back to its original value present before $t = 1.5$ s. Figs. 6a and 6b show waveforms of active powers $P_1, P_2, P_3, P_6, P_8$ and the reactive powers $Q_1, Q_2, Q_3, Q_6$ and $Q_8$, supplied by the sources with conventional droop law. Since the source dynamics are coupled to the network and load dynamics, therefore a oscillatory behavior is observed in active and reactive power supplied by the sources at instant of step change in load power demand. The transients peaks appear in $P$ and $Q$ and after making some excursions, these are finally settled to their steady state values. Due to mismatching in interconnecting line parameters, the reactive power sharing is observed to be poor.

2) Performance of Modified Droop Law: The applicability of the modified droop controller is observed for the same disturbance provided in the load power demand. The values of coefficient $g_p$ for all source are set to $g_{p1} = g_{p2} = g_{p3} = g_{p6} = g_{p8} = 1 \times 10^{-8}$ rad/W. Transient response for active and reactive power demand supplied by these sources is shown in Fig. 6d and 6e. From these waveforms, it is observed that oscillations in $P$ and $Q$ supplied by the sources are less as compared to conventional droop law. Damping of the system is increased due to movement of eigenvalues towards real axis and response of the system is observed to be smooth. From these figures, it is clear that the steady state behavior of the system is not affected by the proposed controller. Therefore, from above discussion, it is inferred that for improved transient response and stabilized operation of microgrid, the proposed droop law between active power and frequency could be used.

3) Performance with high value of active power droop gain: The proposed controller enables the operation of microgrid at high values of $k_p$ to increase accuracy in active power sharing. Fig. 6c shows the response of the system with conventional droop law. The values of active power droop gains for all sources are identical and maintained at $k_p = 0.625$ rad/s – MW. At time $t = 1.5$ s, there is a step increase in the values of active power droop gains. The values of droop gains of sources 1, 2 and 3 are increased form $k_p$ to 10 $k_p$, for sources 6 and 8, these are increased from $k_p$ to 12 $k_p$ and $k_p$ to 14 $k_p$ respectively. Therefore, the operation of microgrid at $t = 1.5$ s becomes oscillatory and the active power supplied by the sources starts increasing without bounds. A instability is observed with higher values of active power droop gains. Fig. 6f shows the operation of the microgrid with proposed droop controller. The system maintain its stabilized operation with increased values of active power droop gains, which leads to more accurate active power sharing.

V. CONCLUSION

In this paper, a droop based active power sharing controllers is proposed to improve the dynamic response of microgrid. Based on the value of $dP/dt$, the proposed controller modifies the value of slope of $P - \omega$ droop characteristic. This modified value of droop gain is responsible for damping oscillations in power shared by sources and leads to improvement in transient response of microgrid. The stability of the system with proposed controller is analyzed using the eigenvalue analysis of the system. Eigenvalue loci plots are used to study the stability of system with variation in various microgrid parameters. Simulation results are included to illustrate the effect of proposed active power sharing controller on the stability and transient performance of the system. The comparison of modified droop scheme with traditional droop control is made on a microgrid test model based on IEEE-14 bus system. The controller reduces the oscillations in power shared by the sources for variation in load power demand and the steady state response of the system remains unaffected.
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### References


