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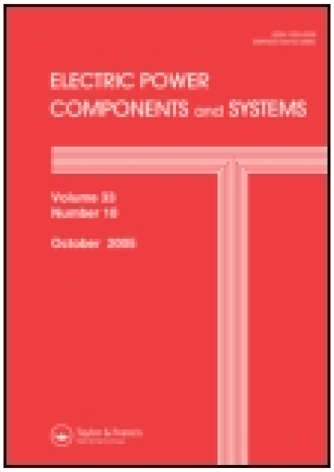

Electric Power Components and Systems
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uemp20

Power Sharing Improvement in Standalone Microgrids with Decentralized Control Strategy

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Published online: 30 Jul 2014.

To cite this article: Hadi Saghafi & Hamid Reza Karshenas (2014) Power Sharing Improvement in Standalone Microgrids with Decentralized Control Strategy, Electric Power Components and Systems, 42:12, 1278-1288, DOI: 10.1080/15325008.2014.927030

To link to this article: http://dx.doi.org/10.1080/15325008.2014.927030

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Electric Power Components and Systems, 42:1278–1288, 2014
Copyright © Taylor & Francis Group, LLC
ISSN: 1532-5008 print / 1532-5016 online
DOI: 10.1080/15325008.2014.927030

Power Sharing Improvement in Standalone Microgrids with Decentralized Control Strategy

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CONTENTS

Keywords: microgrid, dispersed sources, power sharing, reactive power planning, dynamic response, power quality improvement, power system control, power system stability

Received 10 August 2013; accepted 19 May 2014

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Abstract—This article proposes a method that enables ideal sharing of reactive power among converter-based micro-sources in a microgrid with a decentralized control strategy. Power sharing must be properly performed among micro-sources to avoid circulating currents or overloading. Using conventional droop characteristics to achieve power sharing is not satisfactory, as system asymmetry will greatly impact the quality of sharing. In the proposed method, droop characteristic parameters are modified upon a change in system operating point such that ideal sharing takes place after the modification process. Simulation results are presented to show the validity of analysis.

1. INTRODUCTION

The emergence of DRs and DG into distribution networks has opened many new fields of research in power systems. Using DG offers many advantages, such as transmission line expense deferral, increased reliability and efficiency due to the proximity of supply and loads, and the ability of integrating renewable energy resources into a system. The concept of DG has led to another new concept called an MG. An MG is a group of loads and DG units, or MSs, which can operate either as a grid-connected or standalone system and supply the local loads [1, 2].

Extensive research has been carried out in such areas as control, protection, and economical aspects of MGs. The fact that an MG must operate in both grid-connected and standalone (also known as islanded or autonomous) modes brings up many challenging issues for research. In terms of overall control, two main approaches, namely centralized and decentralized control strategies, have been proposed. The centralized control strategy is based on a control center that provides the major control signals for the MSs in an MG. This task is accomplished by using high-speed communication links, which also turns out to be a drawback of centralized approach [3]. In decentralized control strategy, on the other hand, each MS is working autonomously; *i.e.*, its control system is dependent on local available parameters only. This provides more reliable systems in nature [1].

NOMENCLATURE

DG = distributed generation
DR = distributed resource
i_d,i_q = d- and q-axis components of injecting current to microgrid
k_p, k_i = proportional-integral (PI) controller parameters
MG = microgrid
m_p = P-ω droop characteristic slope
MS = micro-source
n_q = Q-V droop characteristic slope
P = micro-source average active power
PI = proportional-integral
P_{IS} = active power in the case of ideal sharing (per unit)
P_n = micro-source rated active power
Q = micro-source average reactive power
Q_{IS} = reactive power in the case of ideal sharing (per unit)
Q_n = micro-source rated reactive power
V = micro-source output terminal voltage
V_0 = microgrid nominal voltage
v_d, v_q = d- and q-axis components of micro-source terminal voltage
α, β = parameters of ω-based droop characteristic during modification process
ω = micro-source frequency
ω_0 = microgrid nominal frequency

A known challenge in MGs with a decentralized control strategy is to properly share active/reactive power among MSs to prevent circulating current among them and avoid possible overloading. On the other hand, many MSs are interfaced to the network using power electronics converters. Therefore, an MG consisting of a converter-based MS can be envisaged as a network of parallel-connected power electronic converters. Consequently, power sharing among MSs is in fact power sharing among parallel-connected converters in an MG with dominant converter-based MSs.

A well-known method adopted to accomplish sharing active/reactive power among multiple converters with no control signal interface is using droop characteristics [1, 4]. This method provides satisfactory results where the connecting lines among MSs are short with negligible or small impedance, as in the case of paralleling multiple uninterruptible power supplies [5, 6]. However, in an MG where the physical and/or electrical distances between MSs are long without any symmetry and sometimes with unknown parameters, the conventional droop method fails to provide satisfactory reactive power sharing among MSs [7–12].

Generally speaking, in droop-based sharing methods, any parameter that is drooped against a global parameter can be ideally shared [4, 7]. Therefore, using a P-ω droop characteristic will naturally result in ideal active power sharing. On the other hand, using a Q-V droop characteristic normally fails to provide adequate reactive power sharing, as voltage is not usually the same at different grid buses due to line impedance and loading pattern variations.

Several methods have been proposed for reactive power sharing improvement among MSs in a standalone MG. The injection of non-characteristic harmonic current was proposed in [7]. The complexity of injection along with power quality degradation and the need for accurate measurement are drawbacks associated with this method. The method proposed in [8] involves the accurate knowledge of network parameters and solving a complicated optimization problem. Some methods provide solutions just for a specific topology [9, 10]. In [9], an integrator is used at the output of the Q-V droop block, which integrates the difference of local and common bus voltage. This requires access to the common bus by all MSs, which is not desirable. A method was proposed in [10] to choose proper Q-V droop parameters based on the local load and voltage drop in the connecting line, which needs the real-time estimation of voltage drop and local load, and optimum sharing is obtained for the common load only. In [11], a method based on Q-(derivative of V) droop was introduced, although it cannot provide ideal sharing for reactive power. Furthermore, it can be shown that when local loads are considered, the reactive power sharing improvement is not significant. In [12], a method was proposed based on periodic modification of Q-V droop characteristics in MSs upon the receipt of a start signal issued by a central controller. However, the proposed method does not provide satisfactory results in all MGs with diverse parameters. Furthermore, the start signal imposes the network to rather large undesirable disturbances, which limits its practical application. The inability to cope with load change during the modification process is another drawback of this method.

This article proposes a method for improving reactive power sharing among converter-based MSs in a standalone MG. Similar to [12], the idea behind the proposed method is based on intermittent modification of the Q-V characteristic. An important feature of the proposed method, as compared with [12], is that the modification process takes the X/R ratio of the lines into consideration. The advantages associated with this improvement are twofold. First, the proposed method can be implemented for MGs with a wide range of X/R ratio without performance degradation. As a result, the proposed strategy can be implemented in standalone MGs with a variety of configurations and with MSs with different control strategies. Second, a substantial improvement in system dynamic response during the modification process can be achieved, as will be shown in Section 7. This improvement also leads to shorter time required for modification process. This article also discusses different approaches for generating a start flag for the modification process. Specifically, a new method is proposed that eliminates an unnecessary start of the modification process.

This article is organized as follows. A brief introduction about decentralized control strategy in standalone MGs along with the structure of an MS controller is presented in Section 2. Section 3 describes the proposed method. The selection of parameters in the proposed method is discussed in Section 4. As the proposed method frequently changes the parameters of the controllers, stability analysis becomes an important aspect, which is addressed in Section 5. Several methods for the generation of a start flag for the modification process are discussed in Section 6. Detailed simulations results are presented in Section 7 to show system performance. A short discussion is given in Section 8 on the networks with resistive-dominant lines. Restrictions associated with ideal reactive power sharing are addressed in Section 9, and Section 10 concludes the article.

2. DECENTRALIZED CONTROL OF MGS

As the proposed compensation method in this article is intended for MGs with a decentralized control strategy, a brief description of this strategy is presented in this section.

As stated in Section 1, the standalone or islanded mode of operation in an MG occurs when the tie-line between an MG and the rest of the utility grid is disconnected, and therefore, local generating units solely supply local loads. In the standalone mode, the most important objectives are proper sharing of active and reactive power among MSs while maintaining acceptable power quality. In this regard, much research has been done on different approaches to achieve these objectives. As a result, two generic methods, namely decentralized and centralized control strategies, have been proposed [3]. In the decentralized control strategy, each MS performs control tasks only based on local parameters without any communication link for exchanging control signals among MSs. This results in more reliable structure. The decentralized approach is also inherently more suitable for implementing plug-and-play MSs, which makes the MG easily expandable.

A typical controller structure for an MS in a standalone MG with a decentralized control strategy is shown in Figure 1. The controller, which is implemented in a synchronous rotating frame, consists of inner (current) and outer (voltage) control loops, droop characteristics, and power calculation blocks. The input to the outer voltage loop is obtained based on the Q-V droop characteristic, as will be explained in the next section. More details about this controller along with its small-signal modeling can be found in [13–15].

3. PROPOSED METHOD

The proposed method along with the associated control structure is described in this section.

3.1. Basic Concepts

It was stated in the introduction that using droop characteristics is a common method to achieve active/reactive power sharing among MSs in a standalone MG with a decentralized control strategy. Conventional P-ω and Q-V droop characteristics are given by

$$\omega = \omega_0 - m_p P, \tag{1}$$

$$V = V_0 - n_q Q, \tag{2}$$

where m_p and n_q are the slopes of P-ω and Q-V characteristics, respectively; ω_0 and V_0 are system nominal frequency and voltage, respectively; and ω, V, P, and Q are system frequency, voltage, active power, and reactive power at the operating point. In the following analysis, it is assumed that the power corresponding to each MS is normalized with respect to its rated power. Therefore, when active/reactive power sharing among MSs is performed ideally, their normalized (per unit) value would be the same for all MSs. The per unit value of active/reactive power in the case of ideal sharing, respectively, is denoted by P_{IS} and Q_{IS} in this article.

In droop-based sharing methods, any parameter that is drooped against a global parameter can be ideally shared [4, 7]. Therefore, using a P-ω droop characteristic intrinsically results in ideal active power sharing, as ω is a global parameter. On the other hand, reactive power is not ideally shared in general, as the voltage in the Q-V droop characteristic is not necessarily the same in all MG buses. This concept is the basis of the proposed "characteristic modification" scheme, as will be described in the following.

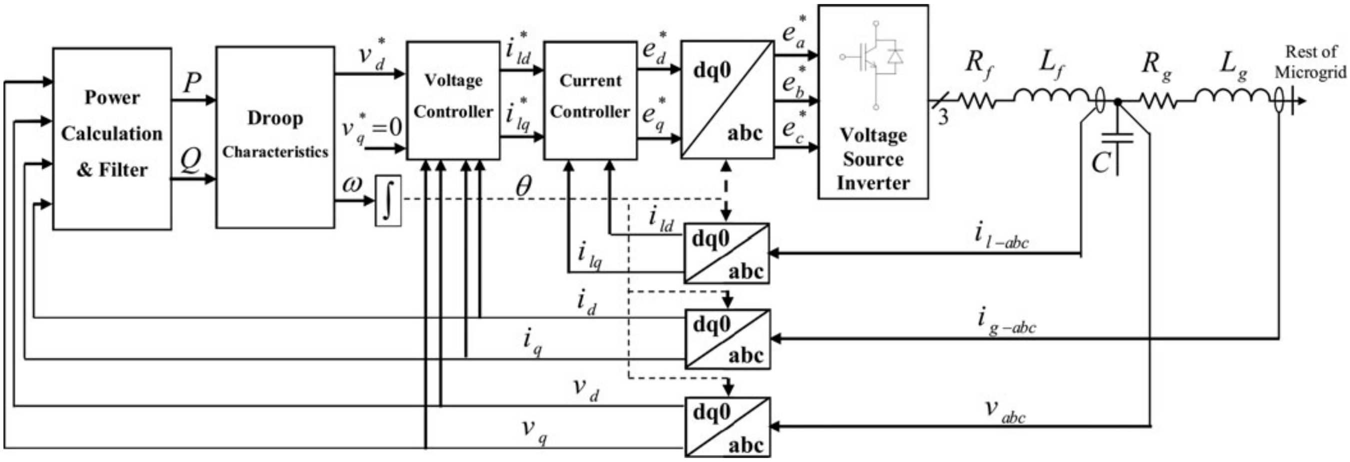

FIGURE 1. A typical controller associated with each MS in a MG with decentralized control strategy.

3.2. Droop Characteristic Modification

To achieve ideal reactive power sharing, the Q-V droop characteristic of each MS is intermittently modified. The modification process is performed by changing either the V_0 or n_q parameters given in Eq. (2), depending on other performance criteria. The modification process starts with changing the P-ω characteristic, given by Eq. (1), to

$$\omega = \omega_0 - m_p(\alpha P + \beta Q), \tag{3}$$

where $\alpha > 0$ and $\beta < 0$ are arbitrary constants that must be equal in all MSs. The criteria for selection of optimum value for α and β to improve MG dynamic performance will be discussed in Section 4. As the term $(\alpha P + \beta Q)$ appears in the new droop characteristic against ω, it can be expected that $(\alpha P + \beta Q)$ will be ideally shared among all MSs after applying this change. In other words, the steady-state value of $(\alpha P + \beta Q)$ tends to become equal in all MSs. This is accomplished by changing the "instantaneous" frequency of each MS. Based on the sign of α and β, this change tends to decrease P in those MSs with Q less than Q_{IS} and increase P in those with Q higher than Q_{IS}.

The change in the P-ω characteristic is accompanied by modifying the parameters of Q-V characteristics (n_q or V_0), given by Eq. (2), such that ideal reactive power sharing is maintained among all MSs. This modification is carried out indirectly by forcing the active power to change back to its initial ideal value, *i.e.*, P_{IS}. Considering that α, β, and $(\alpha P + \beta Q)$ are the same in all MSs, this will lead to Q_{IS} in all MSs; *i.e.*, ideal reactive power sharing takes place.

3.3. Controller Structure

Figure 2 shows how the modification process explained in Section 3.2 can be implemented to modify either n_q or V_0. Consider Figure 2(a), for example, in which n_q is modified, and assume that Q in a particular MS is less than Q_{IS}. Based on the sign of α and β, P tends to decrease in this MS to keep $(\alpha P + \beta Q)$ the same in all MSs. This will create a negative error, which decreases the PI controller output and consequently results in lower slope, n_q. The lower slope of the Q-V characteristic in turn leads to increased Q, which, based on Eq. (3), also results in the increase of P toward the initial value of P_{IS} to maintain $(\alpha P + \beta Q)$ the same among all MSs. The process continues until the error becomes zero and the PI controller provides the new Q-V characteristic parameters. The system then retains the conventional droop characteristics; *i.e.*, the $(\alpha P + \beta Q)$-ω characteristic is switched back to a conventional P-ω characteristic. It is important to note that the operating point of all MSs will be $P = P_{IS}$ before and after switching the characteristics, which results in a smooth and seamless transition at the end of the procedure.

Figure 3 shows the complete block diagram of the proposed controller, which is replaced by the conventional droop controller shown in the front-end stage of Figure 1. As soon as the

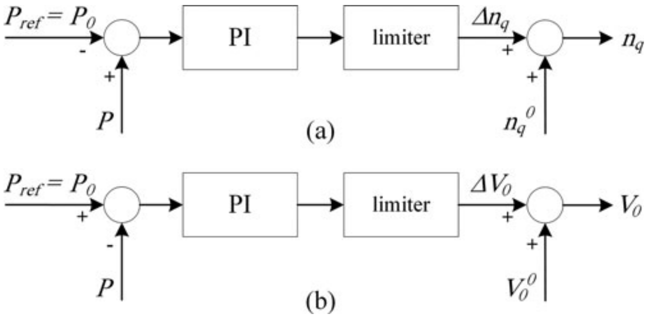

FIGURE 2. Proposed controller for regulating Q-V characteristic coefficients (a) n_q regulator; (b) V_0 regulator.

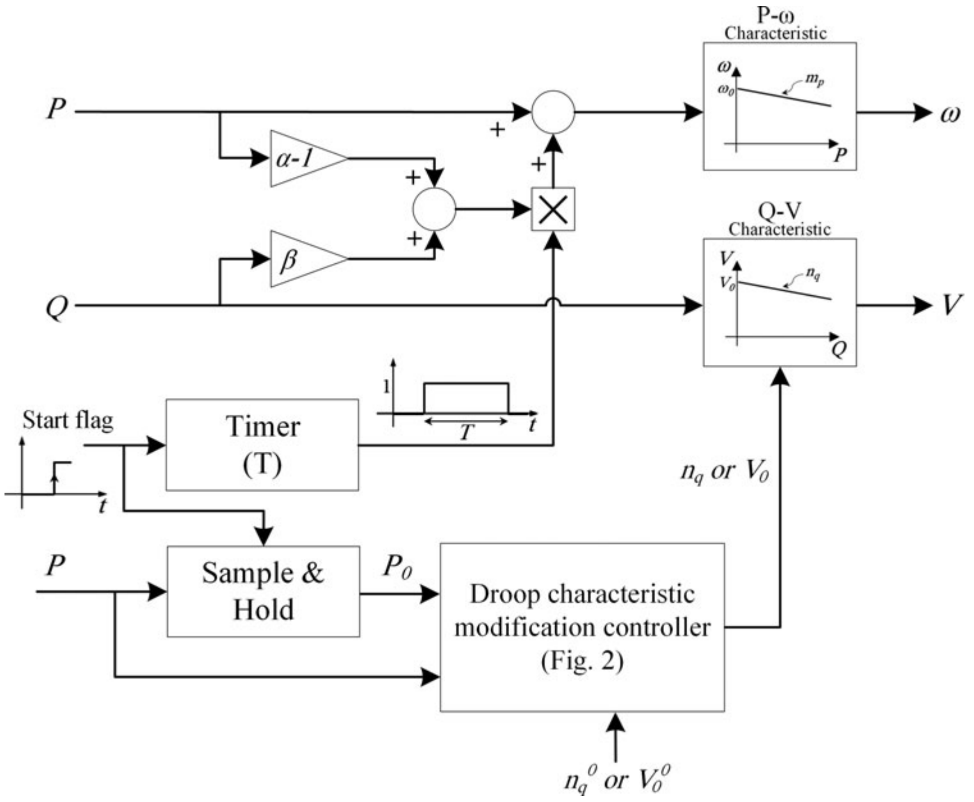

FIGURE 3. Block diagram of the proposed controller which is replaced by droop characteristics in conventional controller.

modification process starts by receiving a start flag, a sample-and-hold block saves the value of $P = P_{IS}$. At the same time, a timer is activated to keep the time T required for the modification process. As long as the timer is on, the P-ω characteristic is switched to a $(\alpha P + \beta Q)$- ω characteristic, and the parameter of the Q-V characteristic is modified using the controller shown in Figure 2. Once the timer interval ends, the droop characteristic is switched back to its conventional form, while the parameters of the Q-V characteristic have been properly modified.

4. PARAMETER SELECTION

It was explained in Section 3 how droop characteristics are changed and modified in the proposed method to achieve ideal reactive power sharing. During the course of these changes, it is normal to expect some dynamics in system behavior. On the other hand, the dynamic behavior of a standalone MG with a decentralized control strategy is highly dependent on the X/R ratio of connecting lines [10, 14–17]. These factors must be properly taken into consideration in designing controllers in the proposed method. In this section, the criteria for the selection of α and β to achieve optimum dynamic response while the system encounters a wide range of X/R ratios are discussed.

Consider Figure 4, which shows a simplified equivalent circuit of an MS connected to the rest of MG. Trivial expressions for active/reactive power exchange are

$$P = \frac{V_1^2}{Z}\cos\theta - \frac{V_1 V_2}{Z}\cos(\delta + \theta), \tag{4}$$

$$Q = \frac{V_1^2}{Z}\sin\theta - \frac{V_1 V_2}{Z}\sin(\delta + \theta), \tag{5}$$

where all parameters are shown in Figure 4 and $Z = R + jX$. After some trigonometric manipulations and considering $Z\cos\theta = R$ and $Z\sin\theta = X$,

$$P = \frac{V_1}{X^2 + R^2}\left[XV_2\sin\delta + R(V_1 - V_2\cos\delta)\right], \tag{6}$$

$$Q = \frac{V_1}{X^2 + R^2}\left[X(V_1 - V_2\cos\delta) - RV_2\sin\delta\right]. \tag{7}$$

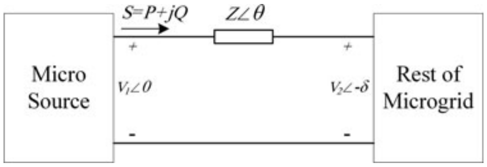

FIGURE 4. A simplified circuit representing a MS connected to the rest of MG.

Combining Eqs. (6) and (7) results in

$$\sin\delta = \frac{XP - RQ}{V_1 V_2}. \tag{8}$$

As δ is usually small, $\sin\delta \approx \delta$, and thus, Eq. (8) can be written as

$$\delta \approx \frac{XP - RQ}{V_1 V_2} \tag{9}$$

Noting that V_1 and V_2 are fairly constant during normal operation, it can be concluded from Eq. (9) that δ and any linear combination of P and Q along with $(XP - RQ)$ have the maximum coupling effect on each other. This implies that setting the $(\alpha P + \beta Q)$ term along with $(XP - RQ)$ increases its coupling with respect to δ and results in optimum dynamic performance. Therefore, a condition for α and β can be obtained as

$$\frac{\alpha}{\beta} = -\frac{X}{R} \Rightarrow \alpha = -\frac{X}{R}\beta. \tag{10}$$

Furthermore, as $(\alpha P + \beta Q)$ must have the same direction as $(XP - RQ)$, one may write

$$\alpha > 0, \qquad \beta < 0. \tag{11}$$

Equations (10) and (11) give the necessary conditions for achieving optimum dynamic performance during the modification process. In the following, additional criterion for selecting α and β is derived.

It was stated in Section 3 that the droop characteristic changes from Eq. (1) to Eq. (3) during the modification process. The term $-m_p P$ in Eq. (1) and the term $-m_p(\alpha P + \beta Q)$ in Eq. (3) determine the deviation of frequency from nominal frequency (ω_0) during system operation. To avoid undesirable frequency variation during the modification process, one can select α and β such that the deviation of frequency remains the same before and during the modification process. This leads to another expression as

$$\alpha P_n + \beta Q_n = \pm P_n, \tag{12}$$

where P_n and Q_n are the rated active and reactive power of the MS, respectively. The negative sign in Eq. (12) denotes the case where $\alpha P_n + \beta Q_n$ is negative. Therefore, α and β can be calculated based on Eqs. (10) and (12) as

$$\alpha = \left|\frac{\frac{X}{R}}{\frac{Q_n}{P_n} - \frac{X}{R}}\right|, \qquad \beta = -\left|\frac{1}{\frac{Q_n}{P_n} - \frac{X}{R}}\right|. \tag{13}$$

Equation (13) provides a guideline for calculating α and β to achieve a fast dynamic response during the modification process. It is worth noting that Eq. (13) takes the X/R ratio of connecting lines properly into consideration.

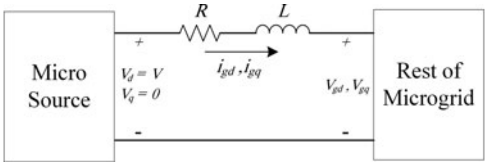

FIGURE 5. The equivalent circuit of Fig. 4 in rotary reference frame.

5. STABILITY ANALYSIS

As stated in Section 2, the MS controller shown in Figure 1 is implemented in the rotating reference frame in which all balanced three-phase quantities are transformed into DC quantities during the steady-state condition, enabling the use of simple but effective PI controllers.

Figure 5 shows the simplified equivalent circuit representing an MS connected to an MG in a rotary reference frame, where v_q is set to zero at the MS terminals [13–15]. The instantaneous active and reactive power [15] at the MS terminals are given by

$$p = \frac{3}{2} v_d i_d, \tag{14}$$

$$q = \frac{3}{2} v_d i_q, \tag{15}$$

where v_d is a d-axis component of the terminal voltage, and i_d and i_q are, respectively, the d- and q-axis components of the MS output current. Based on Figure 1, the instantaneous quantities are passed through a low-pass filter and create input to the droop characteristic blocks. Linearizing Eqs. (14) and (15) around the operating point and assuming a first-order low-pass filter yields

$$\Delta P = \frac{\omega_c}{s + \omega_c}\left(\frac{3}{2} i_{d0} \Delta v_d + \frac{3}{2} v_{d0} \Delta i_d\right), \tag{16}$$

$$\Delta Q = \frac{\omega_c}{s + \omega_c}\left(\frac{3}{2} i_{q0} \Delta v_d + \frac{3}{2} v_{d0} \Delta i_q\right), \tag{17}$$

where prefix Δ represents small signal variation around operating point, subscript 0 denotes operating point quantities, and ω_c is the cut-off frequency of the low-pass filters. Note that although P and Q are average values, they still exhibit some low-frequency dynamics, which are of interest in this analysis. The ω-based droop characteristic during the modification process is given by

$$\omega = \omega_0 - m_p(\alpha P + \beta Q). \tag{18}$$

The V-based droop characteristics during the modification process can be obtained based on Figure 2 and are given by

$$V = V_0 - \left(n_q^0 + k_p(P - P_0) + k_i \int (P - P_0)\, dt\right) Q, \tag{19}$$

where P_0 is the active power before the start of modification, which is equal to P_{IS}; n_q^0 is the Q-V characteristic slope before the start of the modification process; and k_p and k_i are the proportional and integrator coefficients of the PI controller, respectively. Linearizing Eqs. (18) and (19) and writing in the s-domain yields

$$\Delta\omega = -m_p\alpha\Delta P - m_p\beta\Delta Q, \tag{20}$$

$$\Delta v_d = -\left(k_p + \frac{k_i}{s}\right) Q_0 \Delta P - n_q^0 \Delta Q, \tag{21}$$

where Q_0 is the reactive power before the start of the modification process. Substituting ΔP and ΔQ from Eqs. (16) and (17) into Eqs. (20) and (21) provides

$$\begin{aligned}\Delta\omega = &-\frac{3m_p\alpha\omega_c}{2(s+\omega_c)}\left(i_{d0}\Delta v_d + v_{d0}\Delta i_d\right)\\ &-\frac{3m_p\beta\omega_c}{2(s+\omega_c)}\left(i_{q0}\Delta v_d + v_{d0}\Delta i_q\right),\end{aligned} \tag{22}$$

$$\begin{aligned}\Delta v_d = &-\frac{3\left(k_p+\frac{k_i}{s}\right)Q_0\omega_c}{2(s+\omega_c)}\left(i_{d0}\Delta v_d + v_{d0}\Delta i_d\right)\\ &-\frac{3n_q^0\omega_c}{2(s+\omega_c)}\left(i_{q0}\Delta v_d + v_{d0}\Delta i_q\right).\end{aligned} \tag{23}$$

The dynamic expressions governing the MS output current can be written as [14, 15, 18, 19]

$$sL\Delta i_d + R\Delta i_d + \omega_0 L\Delta i_q + Li_{q0}\Delta\omega - \Delta v_d = 0, \tag{24}$$

$$sL\Delta i_q + R\Delta i_q - \omega_0 L\Delta i_d - Li_{d0}\Delta\omega = 0. \tag{25}$$

Equations (22) to (25) describe the dynamic behavior of an MS during the modification process. These expressions can be used to study the dynamic performance of the system during the modification process and also help in designing various system parameters.

Figure 6 shows the variation of dominant eigenvalues versus k_p with $k_i = 0.02$ and $X/R = 0.4$ for a system with parameters given in Table 1. It can be seen that choosing $k_p = 0.0003$ and $k_i = 0.02$ provides a satisfactory result.

6. START FLAG GENERATION

As explained in Section 3, the proposed method requires that a start flag be generated and sent to all MSs for the initiation of the modification process. For successful operation of the proposed method, all existing MSs must simultaneously enter the modification process. Any delay in entering the modification process in a specific MS will result in saving an incorrect P_{IS} for that MS, which eventually leads to error in ideal sharing. In this section, different strategies that can be used for the generation of the start flag are discussed.

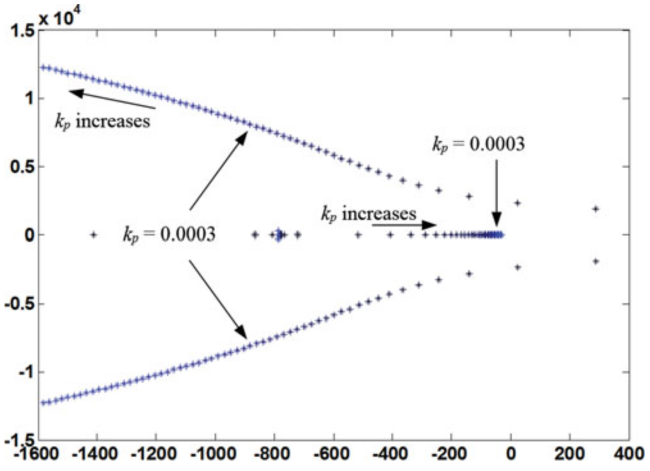

FIGURE 6. The variation of dominant eigenvalues versus k_p with $k_i = 0.02$ and X/R = 0.4 for system of Table 1.

6.1. Periodic Start Flag Generation

In the method proposed by [12], the start signal is generated by a central controller on a periodic basis and sent to all MSs via a low-speed communication link; this ensures simultaneous start of the modification process in all MSs. The modification process will last for a predetermined time set by a timer in each MS. This strategy has some drawbacks. For example, if the interval between modification processes is selected long, large load changes may remain uncompensated for a long time, which is not desirable. On the other hand, if the interval is selected short, very frequent modifications will impose the system to unnecessary dynamics, which is again undesirable. Furthermore, as any load change during the modification process impairs the process and may even lead to system instability, periodic modification will tend to increase the possibility of load change happening during the modification process.

6.2. Start Flag Generation Based on Change of Operating Point

Assume that an MG is operating at a given operating point while active/reactive power is ideally shared. Under this circumstance, any reactive power sharing algorithm, like the one proposed, must be evoked only when the operating point changes. The change in operating point can be detected by different means, such as observing the output power of MSs. This characteristic is the basis for the proposed start flag generation method.

In the proposed method, an appropriate MS that is potentially more influenced by any load change in the MG is selected. The output power of this MS is continuously sampled

		Parameter	Value
Lines		Z1	$0.1951 + j0.1951\ \Omega$ ($0.0676 + j0.0676$ p.u.)
		Z2	$0.0649 + j0.0649\ \Omega$ ($0.0225 + j0.0225$ p.u.)
		Z3	$0.2926 + j0.2926\ \Omega$ ($0.1014 + j0.1014$ p.u.)
Loads		L1, L3, L4	$5.19 + j2.51\ \Omega$ ($1.7994 + j0.8702$ p.u.)
		L2	$2.59 + j1.25\ \Omega$ ($0.8980 + j0.4334$ p.u.)
Grid		Rated voltage	208 V
	Nominal apparent power	$S_{n1} = S_{n2} = S_{n3}$	15 KVA
MSs 1, 2, and 3	LCL filter	Capacitor	1.32 μF (157 p.u.)
		Converter-side inductor	1.2 mH (0.0245 p.u.)
		Grid-side inductor = transformer leakage inductor	161.3 μH (0.0033 p.u.)

TABLE 1. Parameters associated with the MG of Figure 7

and compared with the previous values. If any change larger than a preset threshold is detected, this MS issues the start flag similar to the previous method. While this ensures simultaneous start of the modification process in all MSs, it does not cause unnecessary recall of the process. Also using this method ensures rapid compensation of any significant error in load sharing in a short time after load change.

Any load change during the modification process can ruin the ideal sharing of Q. If this method is used for start flag generation, the MS used to monitor load changes and generate the start flag can detect load change during the modification process and issue a new start flag immediately after finishing the current one. Load changing detection can be done by monitoring the state of the limiter in Figure 2 or by comparing its active power with previously saved P_{IS}.

7. SIMULATION RESULTS

The performance of the proposed method is verified in this section by the help of time-domain simulation of an MG consisting of three MSs and four loads, as shown in Figure 7. Table 1 shows the important parameters associated with this MG.

Figures 8 to 12 show the results of simulations under different operating conditions. In all simulations, the modification process starts at $t = 1$ sec and lasts for 2 sec. Figures 8 and 9 show the variation of active and reactive power before, during, and after modification process for different X/R ratios of connecting lines. The ideal sharing of powers can be observed. Both figures also show the results obtained by the method proposed in [12]. As stated in Section 1, a significant improvement on dynamic response during modification can be observed. Note that such a good dynamic response exists for a wide range of X/R ratios. It is also worth noting that due to significant reduction of dynamics during the modification process, its duration time can be considerably reduced as compared to [12]. For example, it can be seen from Figures 8 and 9 that the dynamic response has been reached in less than 0.5 sec, which can be used to set the timer for the modification process. Lower processing time also reduces the probability of load change during the modification process.

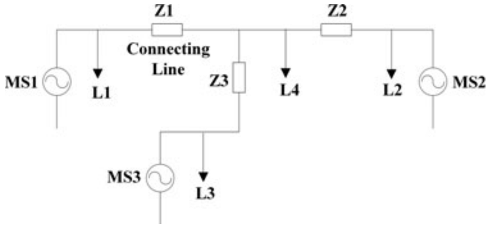

FIGURE 7. The structure of the MG used for the verification of the analysis.

Figure 10 illustrates the voltage at different buses before, during, and after modification corresponding to simulations of Figures 8 and 9. As can be seen, all voltages are in a permissible range in all states. More discussion on the voltage at different buses will be presented in Section 9.

8. P-V CHARACTERISTIC MODIFICATION

It is a common practice to use P-V and Q-ω characteristics to reduce the coupling between P and Q in networks with a low X/R ratio [16, 17]. Under such circumstances, the ideal active power sharing may not be achieved with conventional droop characteristics. Therefore, the proposed method can be used toward the modification of P-V characteristics. Figure 11 shows the simulation results for the system of Figure 7 when the X/R ratio has been reduced to 0.1 and P-V modification strategy has been used. As can be seen, proper sharing of P among MSs has been achieved.

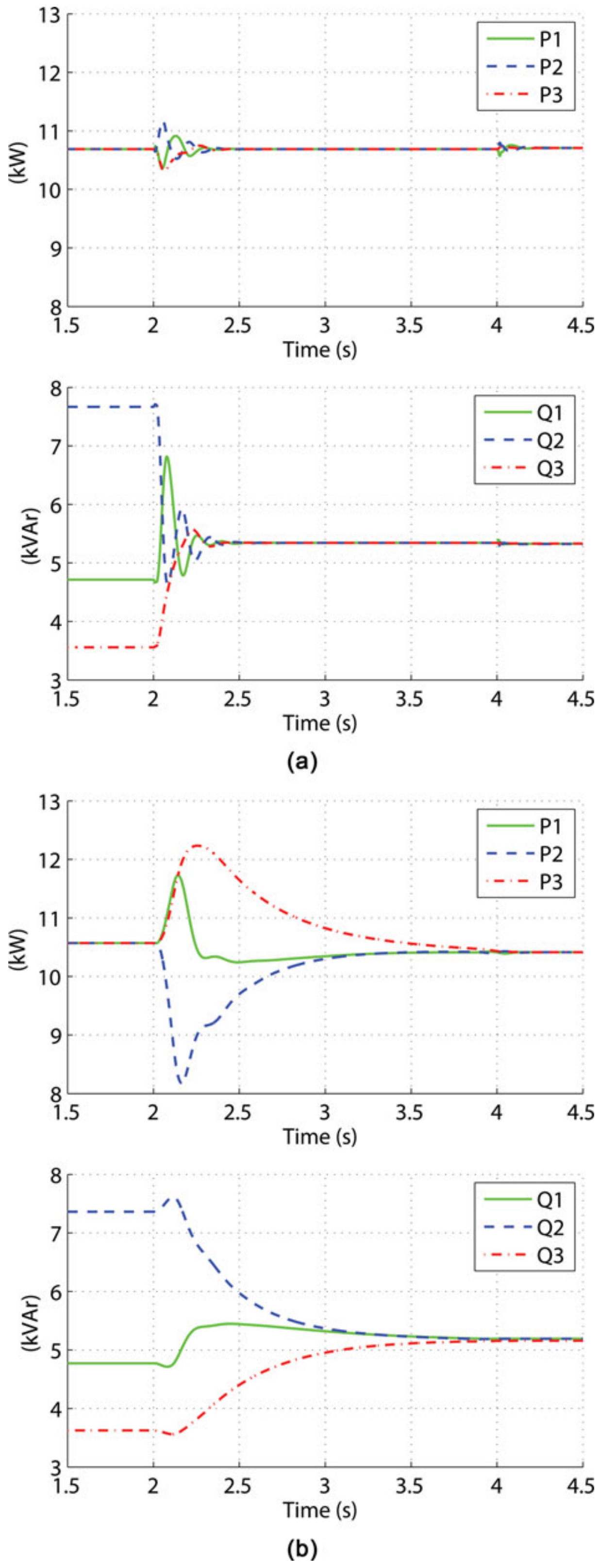

FIGURE 8. Active and reactive power when X/R ratio is 5 (a) using proposed method and (b) using method presented in [12].

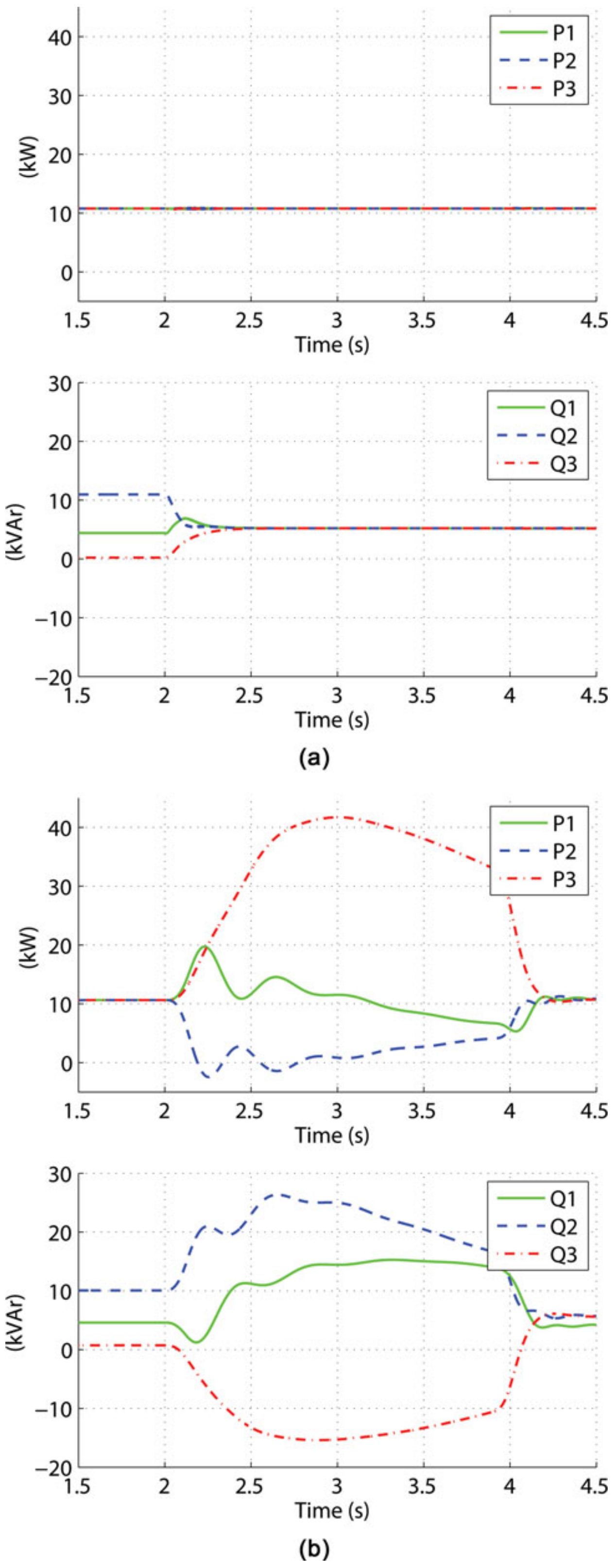

FIGURE 9. Active and reactive power when X/R ratio is 0.4 (a) using proposed method and (b) using method presented in [12].

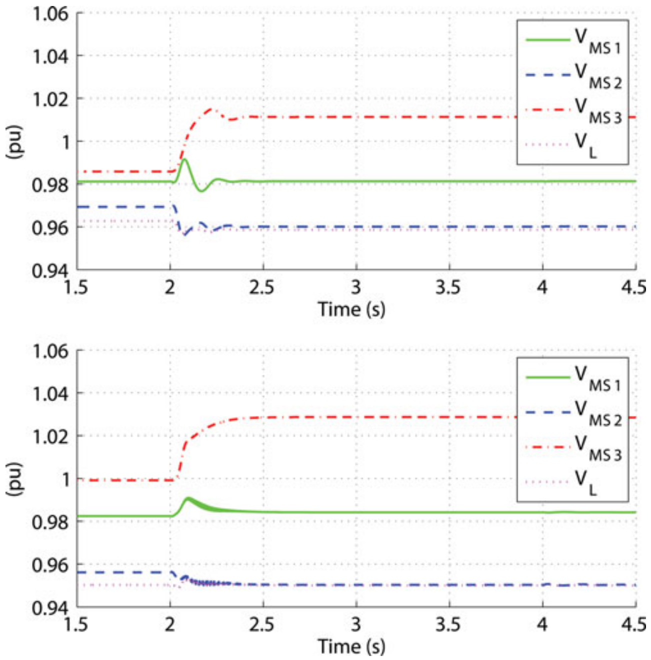

FIGURE 10. Bus voltages when X/R ratio is 5 (top) and when X/R ratio is 0.4 (bottom).

9. IDEAL SHARING RESTRICTIONS

Although ideal sharing among MSs is essential in an MG to ensure balanced and reliable operation of all MSs, other operational constraints in the network must also be taken into consideration when the power sharing is implemented. Among these constraints, those associated with the power quality issue are of major importance and cannot usually be overlooked. For example, considering the relationship between voltage and reactive power in power systems, ideal reactive power sharing may result in unacceptable voltage level at some buses. This problem specifically arises when connecting lines in an MG are asymmetrical and/or too long. When a compromise has to be made between ideal reactive power sharing and keeping power quality indices within a permissible range, it is usually the former that has to be sacrificed.

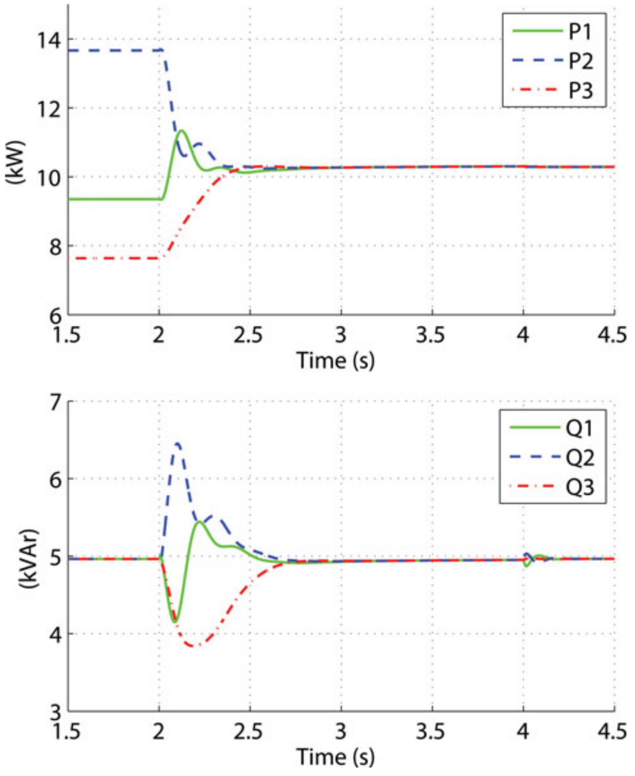

FIGURE 11. Active and reactive power when P-V characteristic is modified using the proposed method.

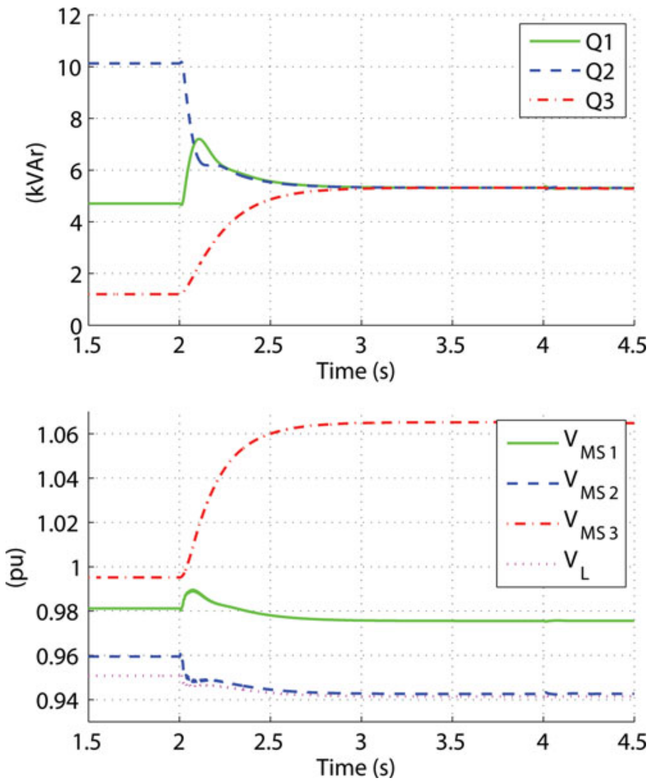

FIGURE 12. Reactive power and bus voltages when the length of line 3 is doubled.

Figure 12 shows the result of ideal power sharing in the system of Figure 7 when the length of line 3 is doubled and the limiter at the controller output in Figure 2 is disabled. It can be seen that ideal reactive power sharing has been obtained at the cost of deviation of bus voltages beyond the acceptable 5% range.

10. CONCLUSION

In this article, a method for ideal sharing of reactive power in MGs with arbitrary configuration was presented. The method is based on the modification of droop characteristic parameters. The modification process starts whenever a change occurs in a network, *i.e.*, a load or generation change. It was shown that using a proper linear combination of P and Q during the modification process would result in a significant improvement of dynamic behavior during the modification process. Stability analysis of the system was presented to indicate stable operation and smooth transition between normal and modification intervals. Extensive simulations were carried out to demonstrate the validity of the analysis. Using the proposed method in a system with highly resistive lines was discussed. A discussion was also presented on the restriction of ideal reactive power sharing due to power quality mandates, specifically the range of acceptable voltage magnitude at different network buses.

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