

Improved Power Sharing Scheme for a Microgrid with Multiple Distributed Generators

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Keywords : distributed generator, droop regulation, microgrid, R/X ratio

Penetration of large amount of distributed generators (DG), liberalized electrical market policy and the reliability concerns of electricity supply are main causes for the origination of microgrid concept in low voltage distribution system. Such a microgrid can be operated in decentralized manner, either in grid connected mode, or in the islanded mode, according to the requirements and/or network obligation. The decentralize or autonomous operation scheme should have the proper power sharing provision among the parallel connected DGs, if possible, without using the control information among them. The real and reactive power controls should be in independent manner, and the DGs should share common real and reactive load in proportion to a pre-determined ratio, regardless of plant parameters. However, MG in distribution network having resistance dominated line interconnection, P - Q control can not be decoupled as in conventional droop. This paper introduces an improved power sharing scheme applicable for the microgrid, without necessitating the communication line among the DGs.

From the well-known network relationship, the power injected by a DG ($E \angle \delta$) to the bus ($V \angle 0$) connected by the impedance ($Z \angle \theta$) between them can be simplified as:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \frac{V}{Z} \begin{bmatrix} E \sin \theta & \cos \theta \\ -E \cos \theta & \sin \theta \end{bmatrix} \begin{bmatrix} \delta \\ e \end{bmatrix} \dots\dots\dots (1)$$

Where, $\delta \approx \sin \delta$ and $e = \Delta E \approx E \cos \delta \approx V$. Decoupling of P and Q is true when $X \gg R$ (with P - f and Q - V droop regulation) or $R \gg X$ (with P - V and Q - f droop regulation). In general the R/X value lies around 2 to 6, so the decoupling is no longer possible with either of underlined droop regulation schemes. As depicted by Eq. (1), the regulation of Q needs the nonlinear control action, though P is fairly linear with phase angle.

In order to get effective power sharing, the proposed scheme introduces virtual impedance in voltage regulation loop, which varies according to the reactive flow through the DG, aiming to reduce the impedance mis-matches among the DGs. Moreover, the feedback of P also helps voltage regulation by minimizing the effect of P in V . The modified V - Q droop regulation, together with the P - f droop as in Eqs. (2) and (3), can provide the proper power sharing among the DGs.

$$\left. \begin{aligned} z_E &= (z_0 + k_1 Q) \\ V &= V_0 + nP - (z_0 + k_1 Q)I \\ \omega &= \omega_0 + m(P_0 - P) \end{aligned} \right\} \dots\dots\dots (2)$$

$$\left. \begin{aligned} \frac{d\delta}{dt} &= (\omega_0 - \omega_{pcc}) + m(P_0 - P) \\ \frac{de}{dt} &= (V_0 - V_{pcc}) + nP - (z_0 + k_1 Q)I \end{aligned} \right\} \dots\dots\dots (3)$$

Simulation results (for the two DG-MG system) of P - Q flow

through the DG1 for different values of line impedance with conventional droop scheme is depicted in Fig. 1. The Q flow is found to be very sensitive to the variation of line resistance in both loading conditions (before and after the step load increase at $t=0.2s$), while P found to be well regulated. In particular, the reactive circulating current increases with increasing values of R/X . It is justified by Eq.(1) because the change of ΔE will cause the change of V and/or E , whereas P is relatively linear with δ . Fig.2 shows the power flow dynamics of DG1 with proposed scheme when step loads are applied to bus#1 and bus#2 at $t=0.2s$ and $0.35s$ respectively. The figure shows the good power sharing when supplying the loads at different load buses at various R/X values. Another notable point of the scheme is that it provides the flexible reactive power sharing among the DGs so that the DGs near the load can share more Q if required. These simulation results validate the applicability of the proposed scheme for low voltage MG system.

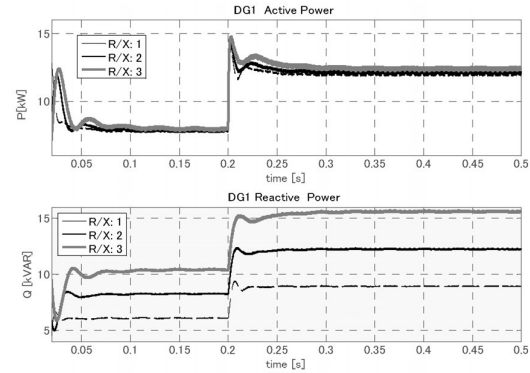


Fig. 1. Power flow dynamics of DG1 (conventional droop scheme)

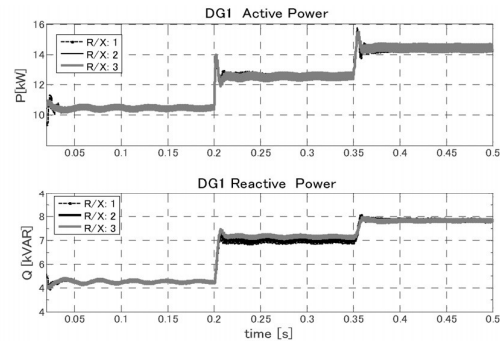


Fig. 2. Power flow dynamics of DG1 (proposed scheme)

Improved Power Sharing Scheme for a Microgrid with Multiple Distributed Generators

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This paper explores the active and reactive power sharing scheme for the parallel operation of inverter interfaced distributed generators (DGs) in a microgrid system. Applicability of conventional wireless control technique, based on P-f and Q-V droop regulations, is also investigated for the load sharing among the DGs with the help of small signal analysis. The conventional droop technique is found to be ineffective in a distribution system with resistive dominated line. In particular, the reactive power becomes highly uncontrolled with large circulating VAR in the presence of high R/X. The virtual impedance concept proposed in the paper intends to address this problem. The so-called virtual impedance is self-regulated variable aiming to reduce the impedance mismatch thereby eliminating the circulating VAR. Consequently, the scheme provides effective active and reactive power sharing among the DGs by adjusting the magnitude and frequency of the voltage at steady-state. Simulation results presented for the two-DGs microgrid system, confirms the validity of the proposed scheme.

Keywords : distributed generator, droop regulation, microgrid, R/X ratio

1. Introduction

Penetration of large amount of distributed generators (DG), liberalized electrical market policy and the reliability concerns of electricity supply are motivating to form autonomously operable 'cluster' in low voltage distribution system. The cluster consist of DGs (eg. Photo-Voltaic, micro-turbine, Fuel cell, micro-hydro etc), electrical loads and local storage system, which is often called microgrid (MG). Such MG can be operated in grid connected mode if required, and can automatically transfers into the islanded mode when there is fault in the upstream side. From the grid side, MG is regarded as a controlled entity within the power system which can be operated as a single aggregate load or, given suitable remuneration, a power source. From the user side, MG is similar to traditional low voltage (LV) distribution network which provides the thermal and the electrical needs, but additionally, reduce emission, enhance the reliability at potentially lower cost of energy supply⁽¹⁾.

In order to provide the electricity at reasonable quality and reliability, the MG operational scheme has many challenges to address. Requirement of power electronic interfaces (dc/ac or ac/dc/ac), presence of diverse nature of DGs, presence of non-dispatchable DGs, requirement to cope islanded and grid connected modes, are few prominent concerns among them.

Besides, the MG operational scheme should have the proper power sharing provision among the parallel connected DGs in the absence of the utility supply, if possible, without using the control information among them. The real and reactive power controls should be independent to each other, and the DGs should share common real and reactive load in proportion to a pre-determined ratio, regardless of plant parameters. The important classes of autonomous load-sharing techniques that have been proposed to

date are: (i) the frequency and voltage droop technique⁽²⁾⁽³⁾, termed as conventional droop scheme, (ii) *P-Q* sharing using communication between DGs⁽⁴⁾, (iii) signal injection technique⁽⁵⁾, and (iv) the adaptive impedance method⁽⁶⁾. Although the active power sharing is satisfactory with these schemes, neither of them could satisfactorily address the reactive power sharing in a distribution network with high R/X value. Utilizing the insights gained from a detailed study of conventional droop techniques, this paper first investigates the applicability of conventional droop scheme in *P-Q* sharing with respect to varying R/X, and proposes a new reactive power sharing scheme by including virtual impedance. The new scheme ensures that DGs on a distributed power network share a common load regardless of the line impedance.

2. Study Scheme

Fig. 1 shows a single line diagram of the study scheme used to investigate possible MG operation and control. The scheme includes the inverter interfaced DGs with different capacity connected to the main grid. Each DG represents a dispatchable source with adequate capacity to meet active and reactive power within limit. Such a dispatchable source includes battery as energy storage interfaced at the converter dc bus to assist the transient power balance. The distribution line is modeled as the lump series R-L elements.

The primovers of the DGs may be the types (fuel cell, micro-turbine etc), which supply the controllable dc power to the inverter. Considering the quite larger time constant of primemover and battery's larger charging-discharging time with respect to the load transient time, the prime-mover and battery are lumped as constant dc voltage source for the time period of interest. Thus, the DGs are represented by a three-phase equivalent of voltage source inverter (VSI) lumped with dc power source. Each phase of the inverter is connected to the system through L-C filter and a lump reactor. The control action of VSI is performed in $\alpha\beta 0$ frames and utilizes the instantaneous power (*P-Q*) control concept

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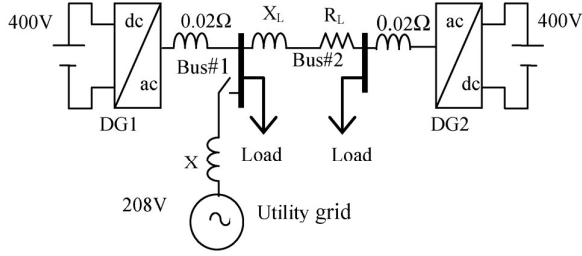


Fig. 1. Single line diagram of study MG system

to specify the magnitude and the phase angle of the voltage⁽³⁾. The microgrid is connected with the utility grid which is represented by ac voltage source with finite impedance.

In this study, the DGs are operating in islanded mode to share the load at the different buses, i.e., the utility grid not connected to the microgrid. If utility grid is to be connected, the power exchange between the microgrid and utility grid can be determined by the appropriate management schemes, tie-line regulation (regulate tie-line power) or unit regulation (regulation of power from each unit) schemes (which is beyond the scope of this study and not included in it). The utility grid is included here to represent the general microgrid-grid interconnection structure owing to open the comprehensive model.

3. Applicability of Droop Regulation

The idea behind the conventional droop control is that the generator themselves can set their instantaneous P-Q flow based upon the decoupled relationship between the P/Q with f/V , so that the power demand within a system can be shared among the generators as pre-specified manner. However in low-volt (LV) and medium-volt (MV) microgrid, the line connection being highly resistive, the decoupling is not possible and hence wireless droop scheme is quite difficult. To get the clear picture of coupling nature of network variables, consider a system as in Fig. 2. For this system, the P - Q supplied by the voltage source to the bus can be represented by Eq. (1).

$$\left. \begin{aligned} P &= \left(\frac{EV}{Z} \cos \delta - \frac{V^2}{Z} \right) \cos \theta + \frac{EV}{Z} \sin \theta \sin \delta \\ Q &= \left(\frac{EV}{Z} \cos \delta - \frac{V^2}{Z} \right) \sin \theta - \frac{EV}{Z} \cos \theta \sin \delta \end{aligned} \right\} \dots \dots \dots (1)$$

Defining control variable as $e = \Delta E \cong E \cos \delta - V$ and $\delta \cong \sin \delta$ we have,

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \frac{V}{Z} \begin{bmatrix} E \sin \theta & \cos \theta \\ -E \cos \theta & \sin \theta \end{bmatrix} \begin{bmatrix} \delta \\ e \end{bmatrix} \dots \dots \dots (2)$$

Clearly, Eq.(2) depicts the fact that P - Q flow through the power source is decoupled with δ - e only in ideal case; namely pure resistive ($\theta=0$) or pure inductive ($\theta=\pi/2$) case. For the high X/R value, traditional droop sharing scheme can be implemented where P - f and Q - V are decoupled. Conversely for highly resistive line coupling, the droop sharing is needed to be reversed. In practice the LV line has R/X ratio lies between 2 to 6. In such case, neither of the above techniques seems to fit.

In order to find proper control scheme, applicability of conventional droop scheme against different values of R/X is checked first, and based upon the limitations, the proper scheme

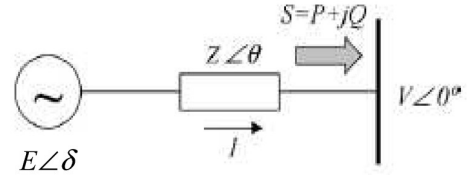


Fig. 2. Voltage source connected to the local Bus

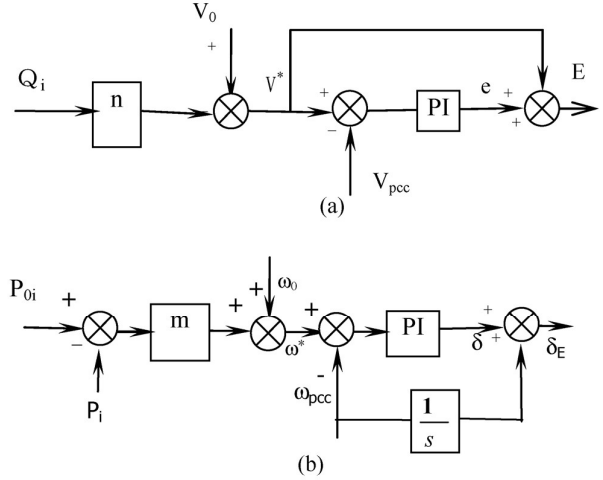


Fig. 3. Block diagram of droop regulation scheme; (a) V-Q droop, (b) f-P droop

will be investigated. The frequency and the voltage droop derived from the conventional scheme is written as⁽²⁾:

$$\left. \begin{aligned} \omega &= \omega_0 + m(P_0 - P) \\ V &= V_0 - nQ \\ \text{with, } m &= \frac{\omega_{no-load} - \omega_{min}}{P_{max}} \\ n &= \frac{V_0 - V_{min}}{Q_{max}} \end{aligned} \right\} \dots \dots \dots (3)$$

Here P_0 , V_0 , ω_0 are the nominal values of active power, voltage and frequency respectively. Similarly, P_{max} , Q_{max} , $\omega_{no-load}$, ω_{min} , and V_{min} represent maximum active power, maximum reactive power, frequency at no-load, frequency at P_{max} , and minimum allowable load voltage of the system respectively. The coefficient m and n are the droop coefficient as defined in the equation. For a microgrid m and n are normally chosen as $\pm 2\%$ and $\pm 5\%$ respectively in per unit system⁽⁸⁾.

The control law for the control variables (δ, e) can be written as:

$$\left. \begin{aligned} \frac{d\delta}{dt} &= (\omega_0 - \omega_{pcc}) + m(P_0 - P) \\ \frac{de}{dt} &= (V_0 - V_{pcc}) - nQ \end{aligned} \right\} \dots \dots \dots (4)$$

Here, ω_{pcc} and V_{pcc} represent the frequency and the voltage at the point of common coupling. It has been reported that by controlling, e , rather than E or V , the impedance mismatch of coupling reactance is minimized⁽⁷⁾. The block diagram of the droop regulation is also shown in Fig. 3.

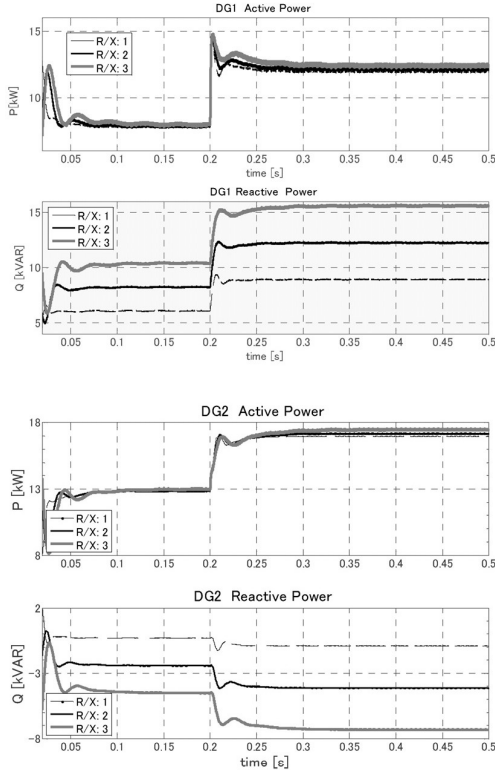


Fig. 4. Power flow dynamics of DGs

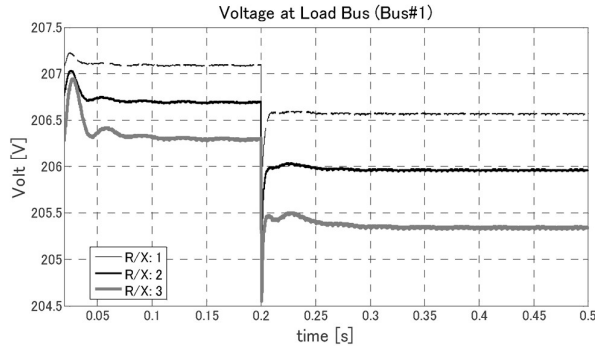


Fig. 5. Voltage dynamics of load bus

From Eqs. (2) to (4) and performing the small signal analysis around the operating point, we have:

$$\frac{d}{dt} \begin{bmatrix} \tilde{\delta} \\ \tilde{e} \end{bmatrix} = \frac{V}{Z} \begin{bmatrix} -mE \sin \theta & -m \cos \theta \\ nE \cos \theta & -n \sin \theta \end{bmatrix} \begin{bmatrix} \tilde{\delta} \\ \tilde{e} \end{bmatrix} \quad (5)$$

Here, the variable with ‘ $\sim$ ’ represents the perturbed values, whereas the quantity with capital letters are the values at the operating point. The characteristic equation of the system represented by Eq. (5) can be written as:

$$\left. \begin{aligned} s^2 + B_1 s + C_1 &= 0, \text{ with} \\ B_1 &= \frac{V \sin \theta}{Z} (Em + n) \text{ and } C_1 = \frac{EV^2}{Z^2} mn \end{aligned} \right\} \quad (6)$$

Since $B_1, C_1 > 0$, the poles always situate at the stable plane indicating that the small signal model of the system is stable for any value of R/X . The choice of m and n is trade-off between the stability and the voltage regulation.

Simulation Results The above scheme is tested to the MG (Fig. 1) under the Matlab[®] simulink platform. The rating of DG1 and DG2 are kept 20 kVA and 30 kVA respectively. The graphs in Fig. 4 shows the dynamics of the power flow through the DGs, with different R/X values of line impedance. Initially a load of $(15+j8)$ kVA was connected to the bus#1 and $(5+j3)$ kVA at bus#2. At $t=0.2$ s another step load of $(8+j3)$ kVA is introduced at the bus#1. It can be seen that P is apparently regulated against different R/X values, whereas the Q is heavily affected by the value. With the increasing value of R/X , the circulating Q increases, though the voltage regulation satisfactory (Fig. 5). The circulating Q is not allowed in the system as it creates the extra burden to the system. Hence the conventional droop scheme is not applicable in the system with resistive dominated line.

4. Introduction of Virtual Impedance

While observing the power follow dynamics in Fig. 4, it can be noticed that the origin of the circulating var is due to the mismatch of impedance between respective DGs and the load bus. Larger the impedance, the smaller is the var flow and vice-versa. Thus the var flow from the DG with smaller interconnecting impedance supplies the circulating var to the DG with larger interconnecting impedance.

To solve this, a large interface inductors can be included between the inverter and the load bus, but they are heavy and bulky. In Ref. (8), resistive compensation is made by adding its effect in setting the reference voltage. However, the amount of resistive part to be compensated is related to the location of load change, which, being the random event, can not be predicted in multi load-buses system. In Ref. (6), authors have proposed the concept of adaptive impedance which varies with the reactive power flow. However, the model is not appealing for the predominately resistive line as it compensates mainly the reactance part. Moreover, the effective impedance sought by the DGs is susceptible with current transient. This paper tries to addressing these limitations by introducing the virtual impedance which varies with Q as in Eq. (7).

$$z_E = (z_0 + k_1 Q) \quad (7)$$

where z_0 is the reference impedance and the k_1 is the constant which determines the sensitivity of Q over z_E . Both parameters are carefully selected depending upon the network and operational circumstances. This impedance compensates for the reactive power difference due to line impedance unbalance by providing the proper reference voltage given by (8).

$$V = V_o + n' P - (z_0 + k_1 Q) I \quad (8)$$

Here n' is the constant coefficient to decouple the effect of active power on V . It is worthwhile to note that the voltage regulation in the Eq. (8) has sought two important considerations; (i) regulation of virtual impedance, (ii) decoupling of the effect of P over V . Thus the set of differential equation to represent the P - Q regulation evolves from Eq. (4) to (9). Notice that though the active power is also affected by the output impedance, it is effectively controlled by self-adjusting of the phase angle alone.

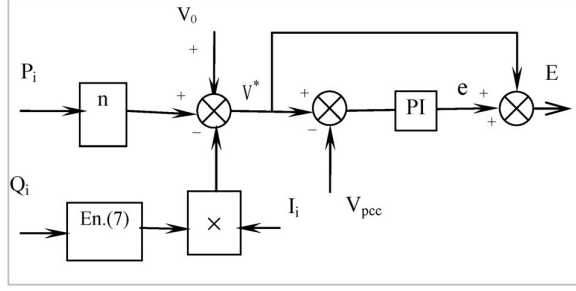


Fig. 6. Block diagram of proposed voltage and reactive power regulation scheme

$$\left. \begin{aligned} \frac{d\delta}{dt} &= (\omega_0 - \omega_{pcc}) + m(P_0 - P) \\ \frac{de}{dt} &= (V_0 - V_{pcc}) + n'P - (z_0 + k_1Q)I \end{aligned} \right\} \dots\dots\dots (9)$$

The block diagram of the proposed scheme is also shown in Fig.6.

4.1 Small Signal Modeling and Control Design Rules

In order to investigate the stability and the transient response of the system, small-signal analysis is performed. The closed-loop system dynamics has been derived, taking into account of well known stiff load-bus approximation⁽⁹⁾. The small-signal dynamics of the phase angle difference and the voltage difference (δ, e) are obtained by linearizing Eqs. (2) and (9), at $\theta=45^\circ$. This is fairly reasonable for small signal analysis and controller gain estimation of the considered microgrid with $R/X > 1$ with inductive coupling ($X/R > 1$) between DG and point of common coupling. Although the complete modeling requires the several low pass filters with signals P , Q , and I , for the sake of simplicity, the low pass filters are excluded from the small signal analysis. It is apparently true, as it will not cause any considerable effect on the closed loop dynamics if the corner frequency of low pass filter is selected quite higher than the dominant poles.

$$\left. \begin{aligned} \frac{d\tilde{\delta}}{dt} &= -m\tilde{p} \\ \frac{d\tilde{e}}{dt} &= n'\tilde{p} - (z_0\tilde{i} + k_1\tilde{q}I + k_1\tilde{Q}\tilde{i}) \end{aligned} \right\} \dots\dots\dots (10)$$

Noting that,

$$I = \frac{S}{V} = \sqrt{(P^2 + Q^2)} / V$$

$$\text{or, } \tilde{I} = \frac{2}{SV} \begin{pmatrix} P\tilde{p} + Q\tilde{q} \end{pmatrix}$$

and substituting the values from Eq. (2) to (10) we get,

$$\frac{d\tilde{\delta}}{dt} = -m\tilde{p}$$

$$\frac{d\tilde{e}}{dt} = \alpha\tilde{p} - \beta\tilde{q}$$

Simplifying,

$$\frac{d}{dt} \begin{bmatrix} \tilde{\delta} \\ \tilde{e} \end{bmatrix} = -\frac{V}{Z\sqrt{2}} \begin{pmatrix} mE & m \\ (\alpha + \beta)E & \alpha - \beta \end{pmatrix} \begin{bmatrix} \tilde{\delta} \\ \tilde{e} \end{bmatrix} \dots\dots\dots (11)$$

$$\text{where, } \alpha = \left\{ n' - \frac{2P}{SV} (z_0 + k_1Q) \right\}$$

$$\beta = \frac{1}{V} \left\{ (z_0 + k_1Q) \frac{2Q}{S} + k_1S \right\}$$

Thus the characteristic equation of the system becomes,

$$s^2 + B_2s + C_2 = 0 \dots\dots\dots (12)$$

with,

$$B_2 = \frac{V}{Z\sqrt{2}} \left\{ mE - n' + \frac{k_1S}{V} + 2 \left(\frac{P+Q}{S} \right) (z_0 + k_1Q) \right\}$$

$$C_2 = \frac{V}{Z^2} \left\{ (z_0 + k_1Q) \frac{2Q}{S} + k_1S \right\}$$

The small signal stability of the system is ensured if $B_2, C_2 > 0$. For a DG the value of n' is comparable to $m \cos \theta$, implying that $mE > n'$. Thus, when the DG is supplying the lagging var, the stability can be achieved for any value of the parameter. But, when the DG is supplying the leading var, the stability is, granted if,

$$\left. \begin{aligned} z_0 + k_1Q_{\max} &\geq 0 \\ \text{or, } z_0 &\geq k_1|Q_{\max}| \end{aligned} \right\} \dots\dots\dots (13)$$

where, $Q_{\max}$ is the maximum leading var supplied by the DG. Thus it can be concluded that the small signal stability is confirmed when Eq. (13) is satisfied.

4.2 Simulation Results

The proposed scheme is tested on the matlab simulink model of the MG (Fig. 1). The loads are assumed to be three phase balanced. The main aim of the scheme is to regulate the reactive power, against the different values of R/X , as the conventional scheme is only able to regulate the active power. The values of necessary parameters used in simulation are shown in Table 1. It should be noted that the rating of DGs are chosen to be same (20 kVA each), which is not necessary in general (the rating of DGs only need to alter the values of m, n). Fig. 7 shows the power flow dynamics through the DGs when the line impedance is changed. Initially the load of $(20+j8)$ kVA at the bus#1 and $(5+j3)$ kVA bus#2 is shared by the DGs. At $t=0.2$ sec another load of $(5+j3)$ kVA is connected to bus#1, which is followed by injection of another load of $(5+j3)$ kVA at bus#2, at $t=0.35$ sec. It can be seen that the active power and reactive power are shared between the DGs, proportional to their ratings, in all conditions, irrespective of the different R/X of line impedance.

Similarly, the voltage dynamics curve shown in Fig. 8. indicates that load voltage is well regulated within the limit, eliminating the circulating var. Another notable merit of the scheme is that the reactive load sharing by the DGs can be made flexible. For example, it is not likely that the DGs which are separated far apart, equally share the common reactive load irrespective of the load location. It is expected that the DGs near the load should share more reactive load than that of DG situated in farther distance, so that the line loss can be reduced (this concept is, however, not effective for the active power sharing as there are many constraint in doing so). The proposed scheme can provide this option by the choice of the z_0 and k_1 . Fig. 9 shows how the individual DG responds with the load change in the nearest load bus. For the ease in analysis purpose, the equal ratings of DGs are selected again. Initially, when both buses were equally loaded, the power sharing between the DGs was equal. When a load of $(5+j3)$ kVA is applied to bus#1, DG1 shares more reactive power than DG2. Again when

Table 1. Parameters used for simulation

$z_0(\Omega)$	k_1	m_1, m_2	n_1, n_2	DG1	DG2	Pf
0.02	10^{-5}	$\pi/20 \times 10^{-3}$	0.3×10^{-3}	20kVA	30kVA	0.9

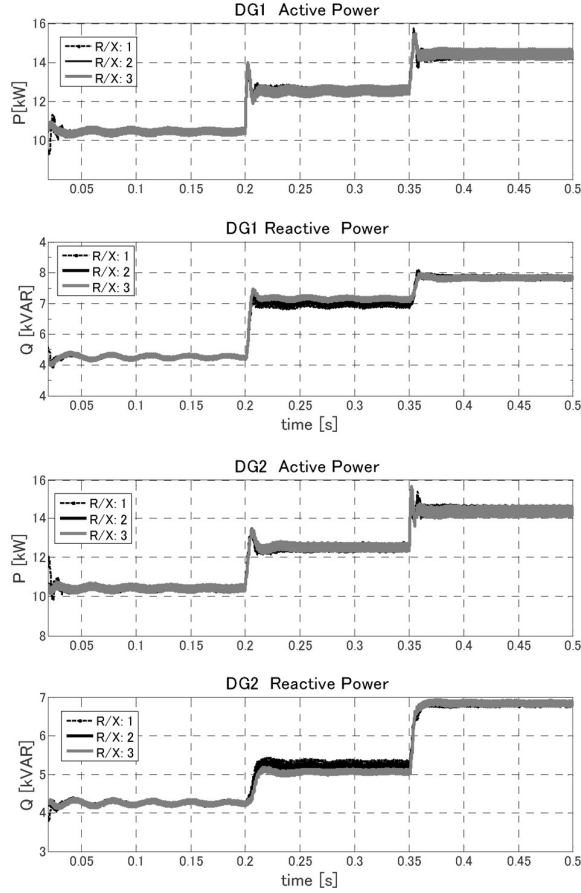


Fig. 7. Power flow dynamics of proposed scheme

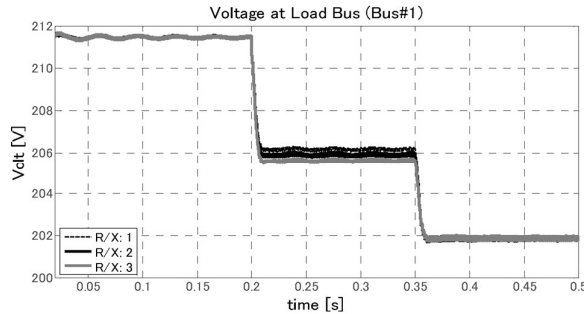


Fig. 8. Voltage dynamics of proposed scheme

another load of $(5+j3)$ kVA is connected to bus#2, DG2 shares more Q than DG1. Thus, the DG situated nearer to the load can be commanded to share more reactive load unless they are overloaded. Active power sharing remain, however, unaffected by the choice of k_f and z_0 , as required.

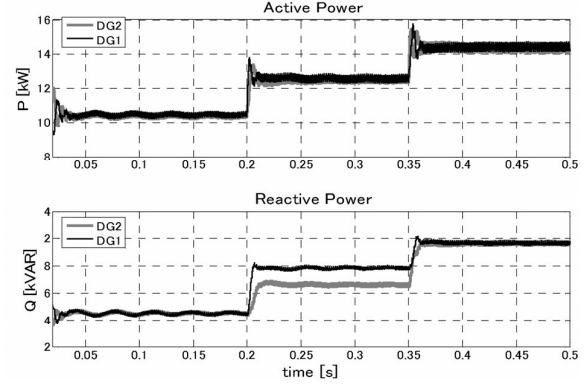


Fig. 9. Active and reactive power sharing

5. Conclusion

This paper proposed a new power-sharing scheme applicable for parallel operating DGs in a distribution microgrid. The scheme is based on the droop regulation, which does not necessitate the communication channel among the DGs. In contrast to conventional droop schemes which are only applicable to line with $X \gg R$, it can provide proper power sharing in distribution microgrid (where $R/X > 2$ in general). Based upon the fact that line parameter (R/X) negligibly affects the active power sharing and highly affects the reactive power sharing, the scheme introduces virtual impedance in $V-Q$ droop keeping the $P-f$ droop unchanged. This allows sharing of active and reactive power without sacrificing frequency/amplitude regulation in the steady-state. Another notable merit of the scheme is that it provides the flexible reactive power sharing among the DGs so that the DGs near the load can share more Q if required (for the purpose of loss reduction).

The simulation results have been reported to validate the proposed control techniques, showing good power sharing when supplying the loads at different load buses at various R/X values. The results justify their applicability to distribution microgrid having inverter interfaced distributed generation units.

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