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Improved Power Sharing among Distributed Generators using Web Based Communication

Ritwik Majumder, *Student Member, IEEE*, Arindam Ghosh, *Fellow, IEEE*,
Gerard Ledwich, *Senior Member, IEEE,* Saikat Chakrabarti *Member, IEEE* and Firuz Zare, *Senior Member, IEEE*

ABSTRACT: This paper investigates the possibility of power sharing improvements amongst distributed generators with low cost, low bandwidth communications. Decentralized power sharing or power management can be improved significantly with low bandwidth communication. Utility intranet or a dedicated web based communication can serve the purpose. The effect of network parameter such line impedance, R/X ratio on decentralized power sharing can be compensated with correction in the decentralized control reference quantities through the low bandwidth communication. In this paper, the possible improvement is demonstrated in weak system condition, where the micro sources and the loads are not symmetrical along the rural microgrid with high R/X ratio line, creates challenge for decentralized control. In those cases the web based low bandwidth communication is economic and justified than costly advance high bandwidth communication.

I. INTRODUCTION

Microgrid can be viewed as cluster of distributed generators connected to the main utility grid. The sources can be inertia-less distributed generators (DG) interfaced through voltage-source-converter (VSC) or inertial sources such as synchronous machine. Decentralized power sharing among DGs can be achieved in a microgrid using droop control method. The real and reactive power outputs of the DGs are controlled by frequency and voltage droop characteristics [1, 2]. In case of converter interfaced sources the power sharing can be achieved through angle droop control [3].

The impact of such load sharing on system stability has been explored in [4-7]. Transient stability of power system with the high penetration level of power electronics interfaced (converter connected) distributed generation is explored in [8]. The robust stability of a voltage and current control solution for a stand-alone DG unit is analyzed in [4] using structured singular values and this result in a discrete-time sliding mode current controller.

Decentralized control method, known as droop control, assumes that the real and reactive power are decoupled in the network and can be controlled by system frequency and voltage magnitude respectively. The above assumption is not valid in a weak system condition, where the DGs and the loads are far from each other or not symmetrical along the microgrid.

The Bulman solar power station [9] servicing two indigenous communities — Bulman and Weemol, is frequently isolated by heavy monsoonal wet season rains. The peak load is supplied with 30 per cent of photovoltaic (PV) generation capacity of a standard diesel power station. Peak power demand in the Northern Territory closely matches solar availability, with the peak occurring early afternoon. As the diesel engines supply all load can not be met by the solar system, including nighttime operation battery storage is not required. This is an example of the scenario under consideration where improvement in power sharing is essential for economic power sharing.

In general, rural electrification should ensure the availability of electricity irrespective of the technologies, sources and forms of generation, but many cannot afford it due to a shortage of resources. Distributed generation is one of the best available solutions for rural microgrid but the location of the sources is very important for optimum power management. In [10] a power electronic converter solution is introduced that is capable of providing rural electrification at a fraction of the current electrification cost for weaker networks which inevitably lead to poor voltage regulation.

The high R/X ratio of low and medium voltage rural network always poses problems to the decentralized power sharing. The strong coupling of real and reactive power in the network leads to an inaccurate load frequency control.

At Anangu Solar Station of South Australia [9], with the off grid renewable connection, 220 kW power is distributed covering 10,000 square km among a number of communities up to 500 people. The minigrid connection at Hermannsburg in central Australia [9] supplies three communities, each with several hundred household (720 kW total power consumption). These are some of the examples of the scenario under consideration where the micro sources and loads are geographically far from each other in a low voltage network with high R/X lines.

A high feedback gain (droop gain) can improve the power sharing but a high gain has negative impact on overall system stability. Unfortunately proper load sharing cannot be ensured even with a high gain if the lines are highly resistive due to the strong coupling of real and reactive power in the network.

To improve the power sharing a low-cost web-based communication system [6-7] is used in this paper. The power quality indices monitored in a distributed measuring system is shown in [11]. A similar philosophy is used here.

The main contribution of this paper is in the improvement of the decentralized control with low cost, low bandwidth web based communication. Both converters interfaced and inertial sources are considered to demonstrate the control scheme with frequency droop control and angle droop control.

R. Majumder, A. Ghosh, G. Ledwich and F. Zare are with the School of Engineering Systems, Queensland University of Technology, Brisbane, Qld 4001, Australia.

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II. WEB BASED COMMUNICATION

The use of web-based communication as a means of monitoring power quality and managing distributed sources has been tried by researchers, and prototype systems have been implemented [17-19]. The main advantages of using web-based communication are as follows [19]:

- Device needed for getting internet connectivity, such as a telephone line and simple modem, cable modem or ISDN line is the only additional requirement in the existing measurement and control system.
- In a standardized internet browser environment with HTML and TCP/IP protocols, the user can work with the graphical user interfaces (GUIs) for different hardware platforms on the same Windows or UNIX system.
- Internet-based applications follow open standards, which makes the exchange of data and expansion of the system easy to implement.
- Internet-based applications are user-friendly, and the human-machine interface does not require extensive training background. Also, no additional software needs to be installed at each PC connected to the system.

The control scheme uses here proposes to use the already existing web-based communication system for power quality monitoring of the DGs. The latest intelligent electronic devices (IEDs) offer built-in communication capabilities that allow for easy interconnection with the DGs, as well as online connectivity with the internet [18]. In case there are not such communication facilities existing, installation of the minimum set of devices for setting internet connectivity, as mentioned above, is required. The proposed control method requires a very low bandwidth, low cost web-based communication system for slow update of the control reference quantities. A low bandwidth web-based data transfer method is used for the minimal communication droop control. The web-based measurement scheme is shown in Fig. 1. The real and reactive power outputs, measured at each DG unit, are communicated to a dedicated website or company intranet with the help of a modem. The measurements are power flow through the line at the DG connection point which is used in the power sharing calculation described in the next section. Assuming that the PQ measurement units are already installed at each DG location, the additional equipment needed for each DG unit are a computer to collect the measurements from local and remote units, and a modem to transmit the measurements to the dedicated website, or to download remote measurements from it.

III. CONTROL SCHEMES

This section describes the control scheme for two scenarios. First a microgrid with only converter interfaced DGs are considered. The decentralized angle droop control [12] ensures the primary power sharing while web based communication system corrects the reference quantities affected by a weak system condition or network parameter. In the second case, a microgrid with both inertial and non inertial DGs is considered. The web based communication improves the system performance while the conventional frequency droop share power among the DGs.

A. *Angle droops and web communication*

A simple system with two DG, as shown in Fig. 2, is considered first to develop the control scheme and then it is extended to a multiple DG scenario.

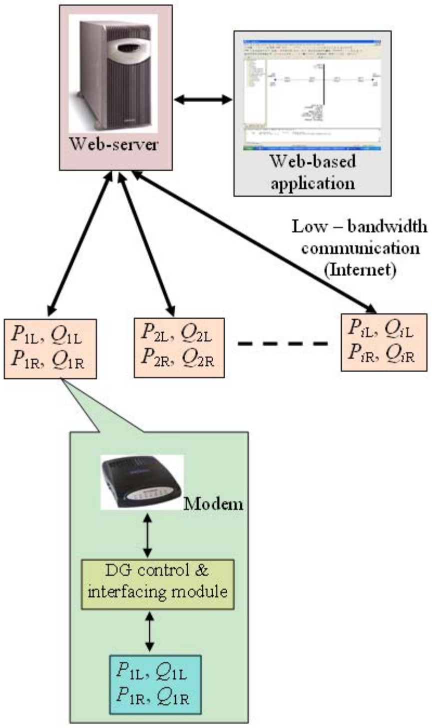


Fig. 1 Web based communication system

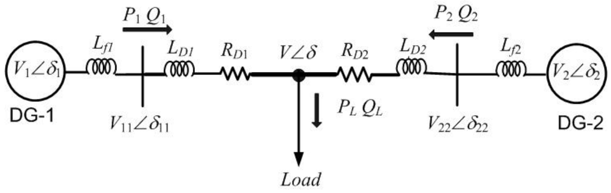


Fig. 2. Simple two .DG system

For small angle difference between the DGs and their respective local buses, the power flow equations of the DGs are given by

$$\begin{aligned} \delta_1 - \delta_{11} &= X_1 P_1 \\ \delta_2 - \delta_{22} &= X_2 P_2 \end{aligned} \tag{1}$$

Similarly the power flow equations over the line for small angle differences can be written as

$$\begin{aligned} \delta_{11} - \delta &= -R_1 Q_1 + X_{L1} P_1 \\ \delta_{22} - \delta &= -R_2 Q_2 + X_{L2} P_2 \end{aligned} \tag{2}$$

where $R_1 = R_{D1}/(V_{11}V)$, $R_2 = R_{D2}/(V_{22}V)$, $X_{L1} = \omega L_{D1}/(V_{11}V)$ and $X_{L2} = \omega L_{D2}/(V_{22}V)$.

From (1) and (2) we get,

$$\begin{aligned}\delta_1-\delta &= X_1P_1-R_1Q_1+X_{L1}P_1\\ \delta_2-\delta &= X_2P_2-R_2Q_2+X_{L2}P_2\end{aligned}\tag{3}$$

The difference between δ_1 and δ_2 is derived from (3) as

$$\delta_1-\delta_2 = X_1P_1-R_1Q_1+X_{L1}P_1-X_2P_2+R_2Q_2-X_{L2}P_2\tag{4}$$

Now the angle droop equation used for both the DGs are

$$\begin{aligned}\delta_1 &= \delta_{1rated}-m_1\times\left(P_1-P_{1rated}\right)\\ \delta_2 &= \delta_{2rated}-m_2\times\left(P_2-P_{2rated}\right)\end{aligned}\tag{5}$$

From (5) we get,

$$\begin{aligned}\delta_1-\delta_2 = \delta_{1rated}-\delta_{2rated}-m_1\times\left(P_1-P_{1rated}\right)\\ +m_2\times\left(P_2-P_{2rated}\right)\end{aligned}\tag{6}$$

Since the ratio of the droop gains m_2:m_1 is chosen as the ratio of the rated power P_{1rated}:P_{2rated}, from the above equation we get

$$\delta_1-\delta_2 = \delta_{1rated}-\delta_{2rated}-m_1P_1+m_2P_2\tag{7}$$

From (4) and (7) we get,

$$\begin{aligned}&X_1P_1-R_1Q_1+X_{L1}P_1-X_2P_2+R_2Q_2+X_{L2}P_2\\ &=\delta_{1rated}-\delta_{2rated}-m_1P_1+m_2P_2\end{aligned}\tag{8}$$

The rated angle of the converter output voltage are selected with active and reactive power output of the converter as

$$\begin{aligned}\delta_{1rated} &= X_1P_1-R_1Q_1+X_{L1}P_1\\ \delta_{2rated} &= X_2P_2-R_2Q_2+X_{L2}P_2\end{aligned}$$

Putting these values in (8), we get

$$m_1P_1 = m_2P_2 \quad\Rightarrow \frac{P_1}{P_2}=\frac{m_2}{m_1}=\frac{P_{1rated}}{P_{2rated}}\tag{9}$$

The power sharing of the DGs are proportional to their rating. This control technique can be extended to multiple DG system. This is discussed below.

Multiple DG System

A multiple DG system is shown in Fig.3, where it is assumed that all the DGs are converter interfaced in this case. The four loads that are connected to the microgrid are shown as *Load_1*, *Load_2*, *Load_3* and *Load_4*. The real and reactive power supply from the DGs are denoted by P_i, Q_i, i = 1,…,3. The real and reactive power flow for different line sections and load demand are shown in Fig. 3. The line impedances are denoted as Z_{Di} (= $R_{Di}+jX_{Di}$), i = 1,…,6. It is to be noted that DG controllers need to measure their local quantities only. The real and reactive power flow measurements into and out of the DG local bus are measured. The line impedance and the loads are assumed lumped.

From the power output of DG-3 we can write,

$$\delta_3-\delta_{L4} = X_3P_3-R_6Q_{3R}+X_{L6}P_{3R}\tag{10}$$

where R_6= $R_{D6}/(V_{33}V_{L4})$ and X_{L6}= $X_{D6}/(V_{33}V_{L4})$. Similarly from the DG-2 power output we can write,

$$\delta_2-\delta_{L3} = X_2P_2-R_4Q_{2R}+X_{L4}P_{2R}\tag{11}$$

The angle difference between the loads can be represented as,

$$\delta_{L3}-\delta_{L4} = -R_5Q_{3L}+X_{L5}P_{3L}-R_6Q_{3R}+X_{L6}P_{3R}\tag{12}$$

From (11) and (12) we get,

$$\begin{aligned}\delta_2-\delta_{L4} = X_2P_2-R_4Q_{2R}+X_{L4}P_{2R}-R_5Q_{3L}+X_{L5}P_{3L}\\ -R_6Q_{3R}+X_{L6}P_{3R}\end{aligned}\tag{13}$$

Similarly the power output of DG-1 can be expressed as,

$$\begin{aligned}&\delta_1-\delta_{L4} = X_1P_1-R_2Q_{1R}+X_{L2}P_{1R}-R_3Q_{2L}+X_{L3}P_{2L}\\ &-R_4Q_{2R}+X_{L4}P_{2R}-R_5Q_{3L}+X_{L5}P_{3L}-R_6Q_{3R}+X_{L6}P_{3L}\end{aligned}\tag{14}$$

It can be seen that only the first term in (13) and (14) are locally measurable. The angle difference shown in (12) can be measured by DG-3 and then communicated to DG-2 and DG-1. As these quantities only modify the reference angle to ensure better load sharing, updates can be done using slower sample rates and a slow communication process can achieve that. Moreover, the first term of (13) and (14) is based on local measurement and ensure the primary sharing instantaneously. Equation (13) can be rewritten as

$$\delta_1-\delta_{L4} = \delta_{1p}+\delta_{11}+\delta_{12}+\delta_{13}\tag{15}$$

where

$$\begin{aligned}&\delta_{1p} = X_1P_1,\quad \delta_{11} = -R_2Q_{1R}+X_{L2}P_{1R}\\ &\delta_{12} = -R_3Q_{2L}+X_{L3}P_{2L}-R_4Q_{2R}+X_{L4}P_{2R}\\ &\delta_{13} = -R_5Q_{3L}+X_{L5}P_{3L}-R_6Q_{3R}+X_{L6}P_{3L}\end{aligned}\tag{16}$$

B. Frequency droops and web communication

In this case, it is assumed that one of the DG (DG-3) is a synchronous machine. The basic power sharing is achieved with frequency droop and the web based communication system improves the performance by correcting the references.

Linearizing (4) we get,

$$\begin{aligned}\Delta\left(\delta_1-\delta_2\right) = X_1\Delta P_1-R_1\Delta Q_1+X_{L1}\Delta P_1-X_2\Delta P_2\\ +R_2\Delta Q_2-X_{L2}\Delta P_2\end{aligned}\tag{17}$$

Since the ω = $d\delta/dt$, taking derivative on both sides of the above equation, we get

$$\begin{aligned}\Delta\omega_1-\Delta\omega_2 = X_1\Delta\dot{P}_1-R_1\Delta\dot{Q}_1+X_{L1}\Delta\dot{P}_1\\ -X_2\Delta\dot{P}_2+R_2\Delta\dot{Q}_2-X_{L2}\Delta\dot{P}_2\end{aligned}\tag{18}$$

From (6) we get, the frequency deviation as

$$\begin{aligned}\Delta\omega_1-\Delta\omega_2 = \Delta\omega_{1rated}-\Delta\omega_{2rated}-m_1\times\left(\Delta P_{1rated}-\Delta P_1\right)\\ -m_2\times\left(\Delta P_{2rated}-\Delta P_2\right)\end{aligned}\tag{19}$$

Let us now choose the reference frequency deviation as

$$\Delta\omega_{1rated} = X_1\Delta\dot{P}_1 - R_1\Delta\dot{Q}_1 + X_{L1}\Delta\dot{P}_1$$
$$\Delta\omega_{2rated} = X_2\Delta\dot{P}_2 - R_2\Delta\dot{Q}_2 + X_{L2}\Delta\dot{P}_2$$

Then comparing (18) and (19), we can write

$$m_1 \times \left(\Delta P_{1rated} - \Delta P_1\right) + m_2 \times \left(\Delta P_{2rated} - \Delta P_2\right) = 0 \tag{20}$$

As the droop gains are chosen as

$$\frac{m_2}{m_1} = \frac{P_{1rated}}{P_{2rated}}$$

We get from (20)

$$m_1 P_1 = m_2 P_2 \quad \Rightarrow \frac{P_1}{P_2} = \frac{m_2}{m_1} = \frac{P_{1rated}}{P_{2rated}} \tag{21}$$

Similar to angle droop the frequency control scheme can be extended to multiple DG system.

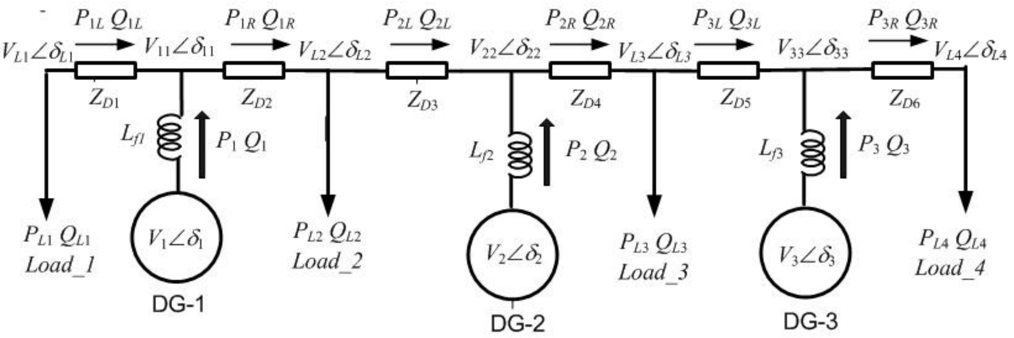


Fig. 3. Multiple DG connected to microgrid.

In both the cases, the primary power sharing is ensured by the droop control while a small correction term is incorporated by the web based communications. Fig. 4 shows the two way communication of the DG and microgrid through the modem. The power monitoring unit sends the real and reactive power measurement to the computer to calculate δ_{11} for DG-1, as shown in (15). The other angle component δ_{12} and δ_{13} are received by the modem and communicated to the DG control unit through the computer.

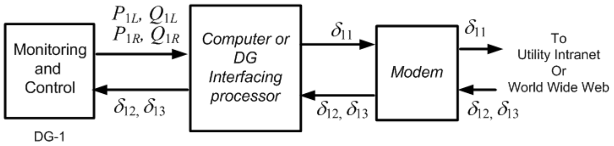


Fig. 4. Communication of the DGs through model

IV. CONVERTER STRUCTURE AND CONTROL

In first case, all the DGs are assumed to be converter interfaced whereas in second case DG-3 is a synchronous machine. In case of converter interfaced sources, the DGs are assumed to be an ideal dc voltage source supplying a voltage of V_{dc} to the voltage source converters (VSCs). The structure of the VSC is shown in Fig. 5. It contains three H-bridges that are supplied from the common dc bus. The outputs of the H-bridges are connected to three single-phase transformers that are connected in wye for required isolation and voltage boosting [13]. The resistance R_T represents the switching and transformer losses, while the inductance L_T represents the leakage reactance of the transformers. The filter capacitor C_f is connected to the output of the transformers to bypass switching harmonics, while L_f represents the output inductance of the DG source. The voltages across the filter capacitors, the currents through them and the currents inject to the microgrid are denoted respectively by v_{cfi}, i_{cfi} and i_{2i}, $i = a,b,c$.

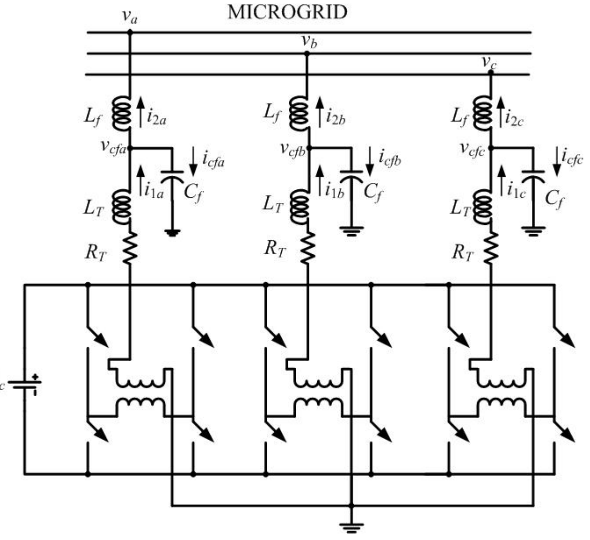


Fig. 5. Converter structure.

From the circuit of Fig. 5, the following state vector is chosen

$$x^T = \begin{bmatrix} i_2 & i_{cf} & v_{cf} \end{bmatrix} \tag{22}$$

A state feedback control law is chosen as

$$u_c = -K\left[x - x_{ref}\right] \tag{23}$$

where K is the gain matrix and x_{ref} is the reference vector for the states given by (22). The gain matrix, in this paper, is obtained through linear quadratic regulator (LQR) design. Based on this control law, the switching actions are taken as

$$\begin{aligned}&\text{If } u_c > h \text{ then } u = +1\\ &\text{elseif } u_c < -h \text{ then } u = -1\end{aligned} \tag{24}$$

where h is a small hysteresis band.

DG Reference Generation

It is evident from (23) that a reference for all the elements of the states, given in (22), is required for state feedback. The reference for the capacitor voltage and current are given by

$$v_{cfref} = V\cos(\omega t + \delta) \tag{25}$$

$$i_{cfref} = V\omega C_f \sin(\omega t + \delta) \tag{26}$$

The reference for the current i_2 can be calculated as

$$i_{2ref} = \left|I_{2ref}\right|\sin\left(\omega t + \delta_{2ref}\right) \tag{27}$$

From Fig. 5, it can be seen that

$$\left|I_{2ref}\right| = \frac{\sqrt{P^2 + Q^2}}{V_{cf}} \text{ and } \delta_{2ref} = \delta - \tan^{-1}(Q/P)$$

In first case, when the DGs share power based on angle droop, the output voltage magnitude and angle is calculated from droop. The instantaneous voltage reference is derived from there and then the references for filter capacitor current and output current are calculated as (26) and (27).

In the second case, where the DGs share power based on frequency droop, V and ω are obtained from the droop equation, to calculate the reference in (25)-(27), the value of δ has to be obtained. The voltage angle controller of the converter generates a rotating angle ϕ_1^* [14] which is equal to $\omega t + \delta_1$. The angle ϕ_1^* is reset after every 2π, i.e.,

$$\omega t_0 = 2\pi = \omega t_1 + \delta$$

Therefore we have

$$\delta = \omega(t_1 - t_0) \tag{28}$$

V. SYNCHRONOUS MACHINE STRUCTURE AND CONTROL

In the second case, DG-1 is assumed to be a synchronous machine. The synchronous machine model given in [15] is used in this paper. The generator field is supplied by a static exciter and automatic voltage regulator (AVR). The transfer function of the exciter-AVR is given by

$$\frac{e_{fd}}{err} = \frac{K_e}{sT_e + 1} \tag{29}$$

where e_{fd} is the field voltage and err is the error in voltage given by $V_{tref} - |V_2|$. K_e and T_e are the AVR gain and time constant, respectively. A mini hydraulic turbine is used as the prime mover [16]. The real and reactive power output of the synchronous machine is controlled by the load –frequency droop and voltage –reactive power droop as the other DGs.

VI. SIMULATION RESULTS

Simulations studies are carried out in PSCAD for various operating conditions. We shall consider two cases. In the first case, all DGs will be considered inertia less and we shall apply angle droop. In the second case, one of the DGs will be a synchronous generator and we shall apply frequency droop.
The nominal system parameters are given in Table –I and the synchronous parameters are given in Table-II.

A. VSC interfaced DGs and angle droop

Let all the DGs be converter interfaced and be controlled by angle droop control. Let us consider the case in which all the three DGs are connected to the microgrid and are supplying only Load_3 and Load_4. While the system in steady state, Load_3 is disconnected at 0.5 s. Fig. 5 (a) shows the power output of the DGs and Fig. 5 (b) shows the power sharing ratios with conventional angle controller (equation 5). In Fig. 5 (b), $P_{ratio\text{-}ij}$ indicates P_i:/P_j. It can be seen that due to high line impedance, the power sharing of the DGs are not as desired (see Table-III). Fig. 6 shows the system response with the proposed controller. The power sharing ratio of the DGs are much closer to the desired sharing and the system reaches steady state within 4-5 cycles.

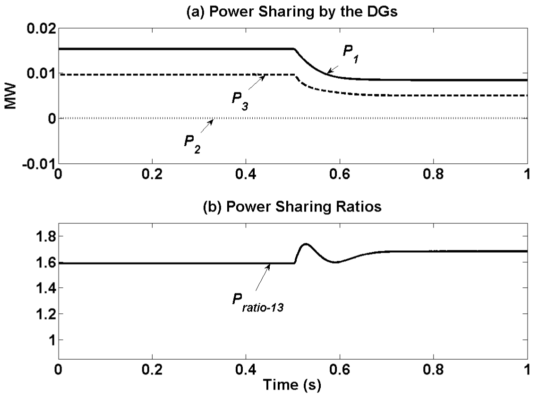


Fig. 5. Power sharing with conventional controller

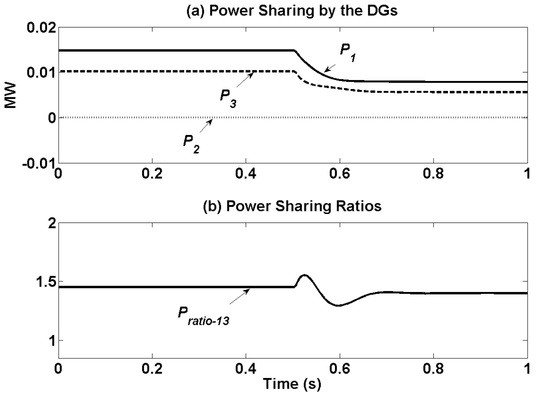
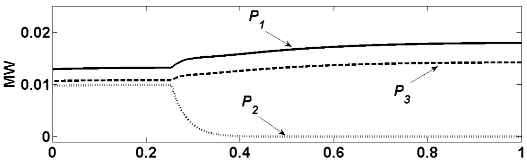


Fig. 6. Power sharing with proposed controller-

To investigate the system response with induction motors connected to the microgrid, a 30 hp motor is connected as Load_3 and a 50 hp motor is connected as Load_4. With the system running in steady state, DG-2 is disconnected at 0.25s. Fig. 7 shows the system response with conventional angle controller. After DG-2 is disconnected, DG-1 and DG-3 supply the total power demand and it can be seen that system takes around 0.3 s to reach the steady state. Due to the high impedance of the line, conventional angle controller fails to share the power as desired (the error is almost 20%). The power sharing with the proposed controller is shown in Fig. 8 and error in power sharing is less than 2%.

(a) Power Sharing by the DGs



(b) Power Sharing Ratios

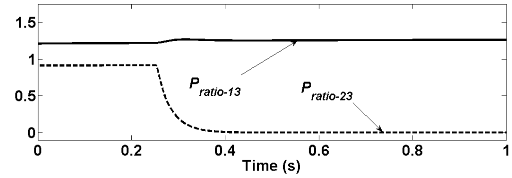
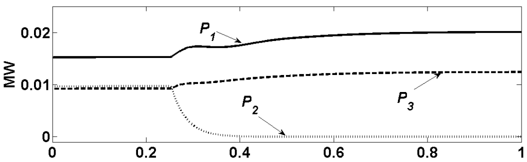


Fig. 7. Power sharing with conventional controller (Case 3).

(a) Power Sharing by the DGs



(b) Power Sharing Ratios

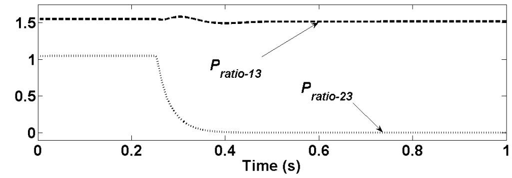


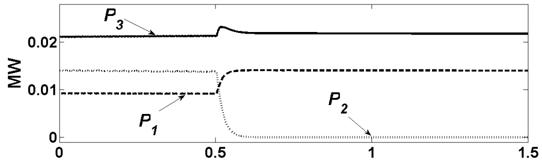
Fig. 8. Power sharing with Controller-2

B. Inertial DG and frequency droop

In this section, DG-3 is assumed to be a synchronous generator. In this case, all the three DGs are connected to the microgrid and supplying Load_2 and Load_3. While the system in steady state, DG-2 is disconnected from the microgrid at 0.5 s. Fig. 9 (a) shows the power output of the DGs and Fig. 9 (b) shows the power sharing ratios with conventional frequency droop controller. It can be seen that the power sharing of the DGs are not as desired. Fig. 10 shows the system response with proposed controller. The power sharing ratio of the DGs, shown in Table-III, are much closer to the desired sharing and the system reaches steady state within 4-5 cycles.

The error in power sharing is shown in Fig. 11. With normal angle droop controller the error is around 12%. The proposed controller makes the error less than 2% as shown in Fig.11 (a). Fig. 11(b) shows the error in case of frequency droop. While the conventional frequency controller shares power with 14.3% error, the proposed control method brings the error down to 2.3%.

(a) Output power of the DGs



(b) Power sharing ratio

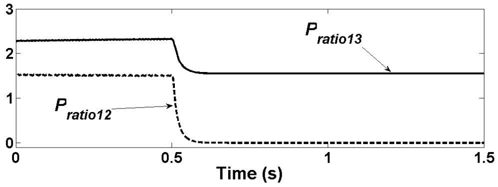
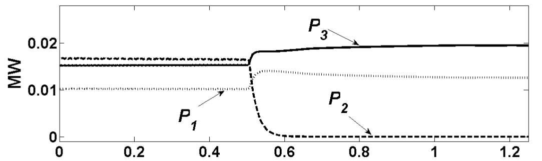


Fig. 9. Power sharing with conventional controller:

(a) Output power of the DGs



(b) Power sharing ratio

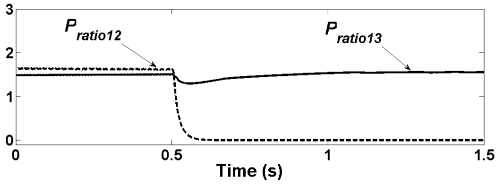
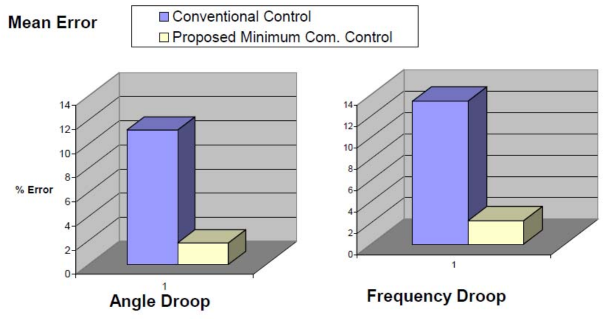


Fig. 10. Power sharing with proposed controller



(a) (b)

Fig. 11 Mean error in power sharing

VII. CONCLUSIONS

This paper demonstrates the possibility of power sharing improvement in a distributed generation with web based communication. The challenges posed by weak system condition and network parameters are overcome by a low cost low bandwidth communication. The decentralized control always ensure the primary power sharing while a correction is made by the web based communication, based on power flow in the microgrid, to reduce the error in power sharing. The proposed scheme shows significant improvement in all the cases both with angle control and frequency control. Depending on the microgrid structure, this could be a very economical and feasible solution for power sharing.

TABLE-I: NOMINAL SYSTEM PARAMETERS

System Quantities	Values
Systems frequency	50 Hz
Feeder impedance	
Z_{D1}	1.0 + j 1.0 Ω
Z_{D2}	0.4 + j 0.4 Ω
Z_{D3}	0.5 + j 0.5 Ω
Z_{D4}	0.4 + j 0.4 Ω
Z_{D5}	0.4 + j 0.4 Ω
Load ratings	
$Load_1$	13.3 kW and 7.75 kVAr
$Load_2$	11.2 kW and 6.60 kVAr
$Load_3$	27.0 kW and 7.0 kVAr
$Load_4$	23.2 kW and 6.1 kVAr
DG ratings (nominal)	
DG-1	30 kW
DG-2	20 kW
DG-3	20 kW
Output inductances	
L_1	0.75 mH
L_2	1.125mH
L_3	1.125mH
DGs and VSCs	
DC voltages (V_{dc1} to V_{dc4})	0.220 kV
Transformer rating	0.220 kV/0.440 kV, 0.5 MVA, 2.5% (L_f)
VSC losses (R_f)	1.5 Ω
Filter capacitance (C_f)	50 μF
Hysteresis constant (h)	10^{-5}
Droop Coefficients	
Angle-Real Power	
m_1	7.5 rad/MW
m_2	11.25 rad/MW
m_3	11.25 rad/MW
Voltage−Reactive Power	
n_1	0.001 kV/MVAr
n_2	0.0015 kV/MVAr
n_3	0.0015 kV/MVAr

TABLE-II: MACHINE PARAMETERS

System Quantities	Values
DG ratings (nominal)	
DG-1	18 kVA, 0.3 to0.95 pf
DG-2	27 kVA, 0.3 to0.95 pf
DG-3	27 kVA, 0.3 to0.95 pf
Droop Coefficients for frequency droop	
Power−angle	
m_1	25 rad/s/MW
m_2	16.67 rad/s/MW
m_3	16.67 rad/s/MW
Voltage−Q	
n_1	0.6 V/KVAr
n_2	0.4 V/KVAr
n_3	0.4 V/KVAr
Synchronous Machine	
Inertia constant, H	0.2 s
Damping constant D	1.0
Direct axis transient time constant T’d0	1.497 s
Quadrature axis transient time constant T’q0	0.223 s
Armature resistance Ra	0.01 pu
Direct axis reactance Xd	0.8 pu
Quadrature axis reactance Xq	0.752 pu
Direct axis transient reactance X’d	0.16 pu
Quadrature axis transient reactance X’q	0.325
Synchronous speed ωs	100π rad/s
Exciter	
Gain Ke	12.0
Time constant Te	0.05 s

TABLE-III: POWER SHARING RATIO

Fig	**Controller**	**Power Sharing Ratio**					
		P_1/P_2		P_1/P_3		P_2/P_3	
	Angle droop	Initial	Final	Initial	Final	Initial	Final
5 & 6	Desired Values	1.5	1.5	1.5	1.5	1.0	1.0
	Conventional	1.32	1.3	1.22	1.2	0.62	0.59
	Proposed Controller	1.59	1.6	1.53	1.54	1.02	1.03
7 & 8	Desired Values	–	–	1.5	1.5	1.0	0.0
	Conventional	–	–	1.22	1.25	0.97	0.0
	Proposed Controller	–	–	1.52	1.51	1.02	0.0
Frequency droop							
9 & 10	Desired Values	1.5	0	1.5	1.5	1.0	NA
	Conventional	1.55	0	2.21	1.6	1.42	NA
	Proposed Controller	1.50	0	1.53	1.61	1.04	NA

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Ritwik Majumder (S'07) received his B.E. in Electrical Engineering from Bengal Engineering College (Deemed University) in 2001 and his M.Sc. (Engg.) degree from Indian Institute of Science in 2004. From 2004 to 2007, he was with Tata Motor Engineering Research Centre in Jamshedpur, India. Siemens Automotive India and ABB Corporate Research Centre, Bangalore, India. Since June 2007, he is a Ph.D. scholar in Queensland University of Technology. His interests are in Power Systems dynamics, Distributed Generation and Power Electronics Applications.

Arindam Ghosh (S'80, M'83, SM'93, F'06) is the Professor of Power Engineering at Queensland University of Technology, Brisbane, Australia. He has obtained a Ph.D. in EE from University of Calgary, Canada in 1983. Prior to joining the QUT in 2006, he was with the Dept. of Electrical Engineering at IIT –Ka npur, India, for 21 years. He is a fellow of Indian National Academy of Engineering (INAE) and IEEE. His interests are in Control of Power Systems and Power Electronic devices.

Gerard Ledwich (M'73, SM'92) received the Ph.D. in electrical engineering from the University of Newcastle, Australia, in 1976. He has been Chair Professor in Power Engineering at Queensland University of Technology, Australia since 2006. Previously he was the Chair in Electrical Asset Management from 1998 to 2005 at the same university. He was Head of Electrical Engineering at the University of Newcastle from 1997 to 1998. Previously he was associated with the University of Queensland from 1976 to 1994. His interests are in the areas of power systems, power electronics, and controls. He is a Fellow of I.E.Aust.

Saikat Chakrabarti (S'06, M'07) obtained the Ph.D. degree in Electrical Engineering from Memorial University of Newfoundland, Canada, in 2006. Currently he is working as a Lecturer in the School of Engineering Systems, Queensland University of Technology, Brisbane, Australia. His research interests include power system dynamics and stability, state estimation, and application of computational intelligence to power system problems.-

Dr Firuz Zare (M'97, SM'06) was born in Iran in 1967. He holds a PhD degree in Electrical Engineering from Queensland University of Technology in Australia. He has worked as a development engineer and a consultant in industry for several years. He has joined the school of engineering systems in QUT in 2006. His research interests are power electronic applications, pulse-width modulation techniques, renewable energy systems and electromagnetic interferences.