Virtual Impedance-based Decentralized Power Sharing Control of an Islanded AC Microgrid

Erum Pathan
Department of Electrical Power Engineering
Universiti Tun Hussein Onn Malaysia
Johor, Malaysia
erumasad79@gmail.com

Mubashir Hayat Khan
Department of Electrical Power Engineering
University Tun Hussein Onn Malaysia
Johor, Malaysia
mubashir.uthm@gmail.com

Haider Arshad
Department of Electrical Power Engineering
University Tun Hussein Onn Malaysia
Johor, Malaysia
haiderarshadkhan@gmail.com

Muhammad Kashif Aslam
Electrical Engineering Department
COMSATS University
Islamabad, Pakistan
kashif_aslam11@yahoo.com

Dawar Jahangir
Electrical Engineering Department
NUCES University
Islamabad, Pakistan
jahangir@gmail.com

Muhammad Asad
Substation Automation Engineer
NG CSD-C, Saudi Electricity Company
Riyadh, Saudi Arabia
csd_sec@yahoo.com

Muhammad Imran Rabani
Department of Electrical Contracting & Maintenance
XERVON, Saudi Arabia
imran.shafaat@xervon-me.com

Abstract-The future of power systems depends on the microgrid (MG) which includes distribution generators utilizing Renewable Energy Resources (RERs) and storage facilities. Decentralized control techniques are more reliable and stable in comparison with centralized controlled techniques. In this paper, a decentralized control strategy is presented for an islanded AC MG system. The control strategy includes improved droop control and virtual impedance. Control strategy with PI controllers to control the voltage and current is implemented to two Voltage Source Inverter (VSI) distribution generation units connected in parallel through a Point of Common Coupling (PCC). Circulating current and power-sharing deviations caused by the mismatched line impedance were taken into account. The proposed control scheme was tested in MATLAB/Simulink. Power-sharing accuracy and circulating current suppression were obtained by implementing the proposed virtual impedance-based decentralized control strategy.

Keywords-PI controller; decentralized control; droop control; virtual impedance

I. INTRODUCTION

Globally, power systems are often overburdened due to the excessive electricity usage. The inclusion of Renewable Energy Resources (RERs) in modern power systems is one of the most popular solutions to cope up with the electricity demand. More and more RERs are being added to the power systems which may cause many critical issues regarding control and management [1, 2]. Microgrids (MGs) may face different challenges with different operating modes. In the islanded mode, power sharing according to the capacity of the inverter-based DG units connected in parallel, and combined with loads to form a complete system, is not accurate, whereas in the connected mode, the case is not same [3]. Voltage Source Inverters (VSIs) are solely responsible for voltage and frequency control in islanded MGs. Different kinds of issues may occur in isolated MG, for example voltage and frequency errors, line impedance mismatch and the consuquent production of circulating current [4, 5]. When many DG units are operating in parallel in the same system, the overall impact of circulating currents could be very high and could damage the entire system. Unlike the traditional power systems, in which the circulating currents do not affect the system due to the large synchronous generators, in MGs even the presence of the smaller line impedance is considered to be a serious issue that needs to be handled carefully [6]. In the literature, virtual impedance is implemented, most of the times, in order to get

Corresponding author: Erum Pathan

rid of circulating currents. Droop control which has the ability to operate without a communication link has been implemented with virtual impedance [7, 8] to achieve power sharing accuracy. Virtual impedance-based techniques need to have line impedance exact values which are very difficult to calculate at every instant. In [11, 12], the dependency of line impedance was eliminated by utilizing a method which can control droop gains. Unfortunately, the droop coefficient regulation technique has some serious concerns related to voltage and system stability. A frequency controller with nonlinear matrix inequality was presented to ensure the stability of the system in [9] and the improved droop-based control with autonomous operation for AC-DC MG control was proposed in [10]. Modification in droop with complex line impedance has been implemented in [13] for power sharing accuracy but the system stability and reliability was not considered. An adaptive virtual impedance multi-agent consensus control scheme was presented in [14]. The scheme significantly improves power sharing accuracy but with slow system response. However, control techniques related to power sharing control and circulating current suppression have different issues.

This paper presents an improved droop-based simple control technique for power sharing and circulating current suppression in AC islanded MGs. The proposed control technique is implemented to two VSI units and their virtual impedance is also considered. Proportional Integral (PI) controllers control the voltage and current for accurate power sharing between the two VSIs connected in parallel at the Point of Common Coupling (PCC). Moreover, the circulating currents between the VSIs are suppressed in the proposed control scheme.

II. SYSTEM DESCRIPTION

This paper presents a virtual impedance-based, voltage source inverter, VSI-based islanded MG power sharing control scheme which is implemented on two DG inverters as shown in Figure 1. The system is composed of LCL output filters and distribution lines. It worth mentioning, that the system is designed considering ideal DC voltage sources where storage and losses are not considered. The system has resistive inductive load which is shared by two DG inverters. Figure 1 shows the islanded MG with two identical DG inverters connected to the LCL filter, virtual impedance, and distribution lines. Both the DG inverters are connected to the PCC and a load is connected directly to the PCC.

III. REACTIVE POWER ANALYSIS AND DROOP CONTROL

In inverter-based systems, more and more DG units are connected in parallel to increase the capacity of the MG. A single phase of parallel connection of the MG is given in Figure 2. Input voltage and currents for DG1 and DG2 with their respective power angle δ and impedance angle θ are: $V_{o1}<\delta_1$, $V_{o2}<\delta_2$, $I_1<\theta_1$, and $I_2<\theta_2$ respectively. The active and reactive powers (P and Q) for the i^{th} inverter are expressed in (1), (2).

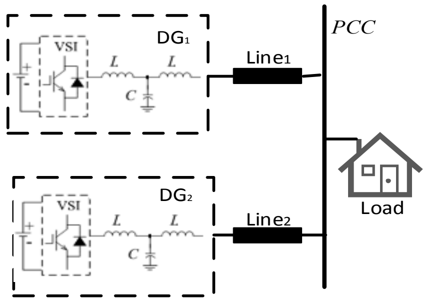


Fig. 1. Islanded MG.

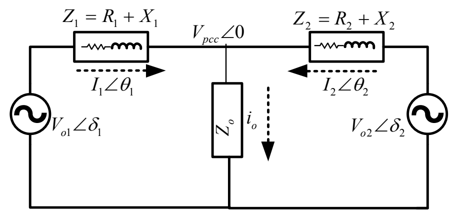


Fig. 2. Two parallel inverters' connection with PCC.

$$P_i = \frac{V_{oi}}{R_i^2 + X_{Li}^2}[R_i(V_{oi} - V_{PCC}\cos\delta_i) + X_{Li}V_{PCC}\sin\delta_i \quad (1)$$

$$Q_i = \frac{V_{oi}}{R_i^2 + X_{Li}^2}[-R_iV_{PCC}\sin\delta_i + X_{Li}(V_{oi} - V_{PCC}\cos\delta_i) \quad (2)$$

When X_V+X_L is much greater than R and the angle δ is very small, the above equations can be simplified as:

$$P_i = \frac{V_{oi}V_{PCC}\cos\delta_i}{X_i} \quad (3)$$

$$Q_i = \frac{V_{oi}(V_{oi} - V_{PCC})}{X_i} \quad (4)$$

where $X \simeq X_V + X_L$. P and Q are providing the conventional droop basics which are expressed as:

$$\omega_i = \omega^* - m_iP_i \quad (5)$$

$$V_{oi} = V_o^* - n_iQ_i \quad (6)$$

where ω*, V*, and n, m are the nominal frequency, and voltage and droop coefficients respectively. Droop control is good for active power sharing accuracy while reactive power sharing is not easily achieved because of the effect of line impedance mismatch.

IV. PROPOSED VIRTUAL IMPEDANCE-BASED CONTROL

A. *Inner Voltage and Current Loop*

For the sake of voltage regulation, a proportional resonant controller is employed. Figure 3 shows the voltage and current control loops with the filter. The transfer function for the PI controller is:

$$G_V = K_{pv} + \frac{2K_{iv}\omega_c s}{S^2 + 2\omega_c s + \omega_f^2} \quad (7)$$

$$G_I = K_{pi} \quad (8)$$

where K_{pv} and K_{pi} are related to the controller (PI) gains. The closed loop transfer function with no virtual impedance is given as:

$$V_c = G(s)V_{ref}^* - Z_o(s)I_o \quad (9)$$

where $G(s)$ and Z_o are voltage gain and output impedance respectively.

$$G(s) = \frac{G_V G_I(1+sC_f R_d)}{S^2 L_f C_f + s(R_f C_f + G_I C_f(R_d G_V + 1) + R_d C_f) + G_I G_V + 1} \quad (10)$$

$$Z_o(S) = \frac{(SL_f + R_f + G_I)((1+sC_f R_d)}{S^2 L_f C_f + s(R_f C_f + G_I C_f(R_d G_V + 1) + R_d C_f) + G_I G_V + 1} \quad (11)$$

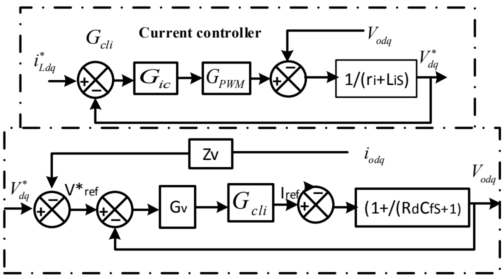


Fig. 3. Voltage and current control and impedance loops.

A. Virtual Impedance Loop

For frequency and voltage magnitude regulation, conventional droop control is commonly recommended, which may be in the form of P-ω or Q-V in MG control for medium voltage networks. In medium voltage MGs, the behavior of the lines is predominately inductive. Considering the low voltage MGs, the predominant inductive behavior does not exist, so the conventional droop control is not very effective while the mismatch in line impedance makes the control system more complicated. Complex virtual impedance is proposed to mitigate line impedance mismatch and power sharing accuracy can be attained. Voltage reference is adjusted by utilizing the virtual impedance.

$$V_{\mathrm{Re}f}^* = V^* - I_o Z_V(s) = V^* - I_o(R_V + R_{vd} + sL_V) \quad (12)$$

From (12), Z_o^* can be written as:

$$Z_o^*(s) = Z_o(s) + G(s)(R_V + R_{vd} + sL_V) \quad (13)$$

The overall block control diagram with the virtual impedance is shown in Figure 4. The droop control and the virtual impedance are utilized to overcome mismatch in line impedance and mitigate the circulating current.

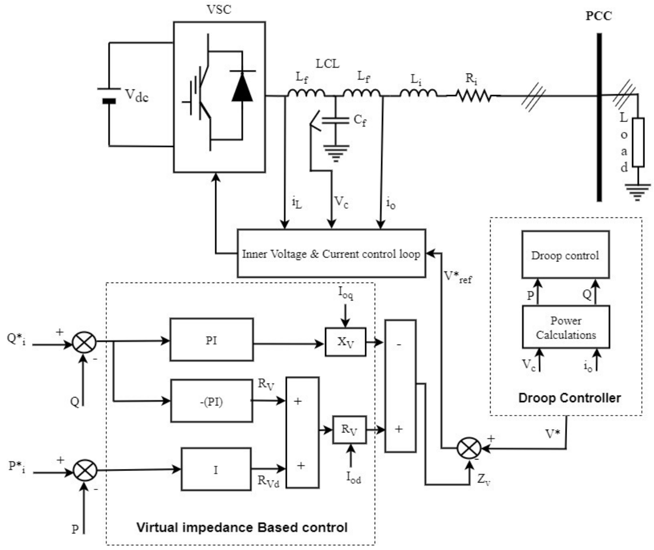


Fig. 4. Virtual impedance-based control.

The impact of the virtual impedance as per the parameters given in Table I can be seen in the diagrams given in Figures 5-6. The output voltage of each unit connected in parallel successfully tracks its respective reference with negligible phase delay. With the proper voltage tracking and voltage controller design considering the complex virtual impedance given in the above equations, proper power sharing can be achieved.

TABLE I. SYSTEM PARAMETERS

DC voltage	700V
Line voltage	311V
Inverter side resistance	100mΩ
Grid side inductor	1.5mH
Inverter side inductor	1.5mH
Capacitor	25μF
Line impedance 1	0.125+j0.396Ω
Line impedance 2	0.085+j0.293Ω
Virtual impedance 1	0.049+j0.191Ω
Virtual impedance 2	0.06-j0.083Ω
Virtual impedance 3	0.029+j0.081Ω
Virtual impedance 4	0.029+j0.081Ω
Voltage controller gains	Kp=1.796 Ki=1.21 $*10^3$
Current controller gains	Kp=0.237 Ki=1.62 $*10^3$
DG1 and DG2 AC MG load power rating P_{L1}	500W, 50VAR
P_{L2}	500W, 50VAR
P_{L3}	3× (500W, 50VAR)

V. SIMULATION RESULTS

The proposed control scheme was tested under in MATLAB/Simulink. The control strategy and the sub model are shown in Figure 5(a)-(b). The MATLAB/Simulink model is designed for three phase ideal voltage sources with power and control section. LC Filter 1 and LC Filter 2 are connected to the VSI 1 and VSI 2 respectively with common loads at the PCC. The utilization of virtual impedance ultimately enhances the power sharing accuracy in the two DG inverter model and suppresses the circulating current.

In the proposed control, the predominating inductive output impedance is considered. The simulation results are taken at different time intervals to illustrate the effectiveness of the proposed control technique. Three different time intervals were taken into consideration:

- From 0 to 1s, the system results are taken without using any virtual impedance loop, only the droop control is considered.
- From 1 to 2s, the virtual impedance Z_{V1} is applied. The addition of the virtual impedance compensates the output line impedance.
- From 2 to 3s, the virtual impedances Z_{v2}, Z_{v3}, and Z_{v4} are applied to the system. At the same time interval, an additional load equal to three times the previously connected load is applied to the system to prove the validity of the proposed control system for two parallel connected inverters.

The virtual impedances are added in the DG inverters in such a way that Z_{V1} and Z_{V4} are added in DG inverter 1 in order to compensate the output impedance mismatch and Z_{v2} and Z_{v3} are added to DG inverter 2. It can be seen in Figure 6 that the proposed control scheme is working properly and tracks the reference currents while enabling the two DG inverter systems to share power accurately. Thus, the system voltage quality is maintained. Voltage and current waveforms are given in Figure 6(a)-(b). The voltage remains the same and accurate even when the virtual impedance loops are added after 1s. Moreover, the voltage stays the same when the load is increased (Table I). Nevertheless, the current waveform is accurate at all the different conditions applied to the MG system. The current waveform is stable even after the addition of the load.

(a)

(b)

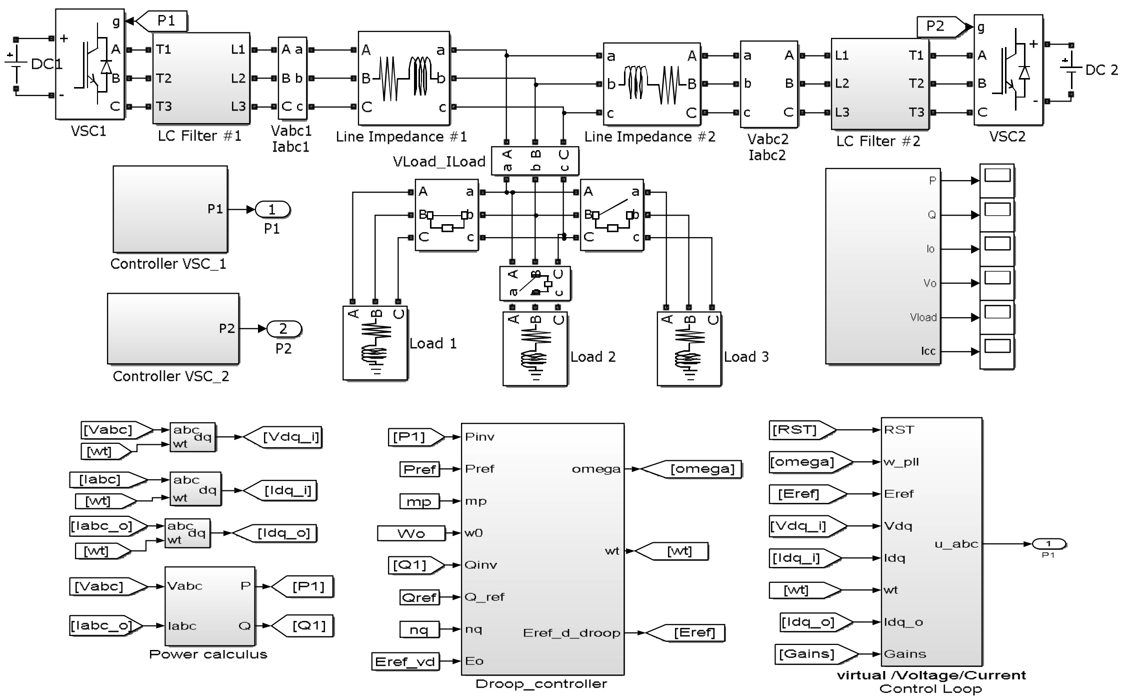
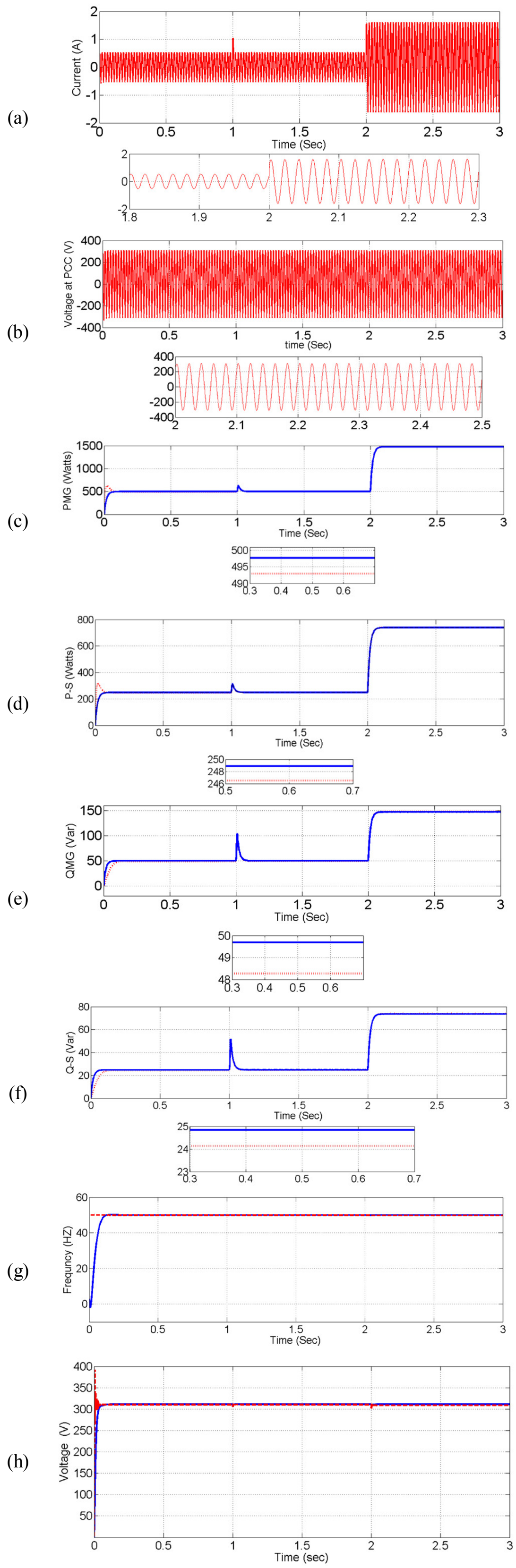


Fig. 5. Simulation (a) model of the parallel inverter and the proposed controller, (b) submodel of the VSC of the proposed controller.

In Figure 6(c), the MG total active power accuracy is shown. During 0-1s, the sharing is not accurate because there is no virtual impedance. There are some fluctuations and the same is observed just after the 1-2s interval. Droop control having P-f, can easily attain active power sharing accuracy. After 2s, the power is increased along with the additional load, but is still accurate as per the load. In Figure 6(d) the MG power sharing accuracy starts after 1s because during 0-1s there is no virtual loop. After 1s, the virtual loop is added and sharing is accurate. After 2s, when the triple load is added, MG reactive power and sharing of reactive power are shown in Figures 6(e)-(f). Before the addition of the virtual impedances the power sharing during 0-1s was not accurate. When virtual impedance was added (after t=2s), the power sharing of both the DG inverters is accurate despite their different output impedances. During the 2-3s time interval, the reactive power sharing remains accurate even after the addition of the triple load. Figures 6(g)-(h) show the accuracy of the voltage and frequency stability when there is convention setting. After the virtual impedances were added, the voltage drop was lower than the voltage drop after 2s because of the additional load. The circulating current is shown in Figure 6(i). It can be seen clearly that during 0-1s there are significant fluctuations and the circulating current is higher. During the 1-2s time interval and after the addition of the virtual impedances, the circulating current is approximately 0. From t=2s, when the additional load was added, it can be seen that the circulating current is suppressed effectively.



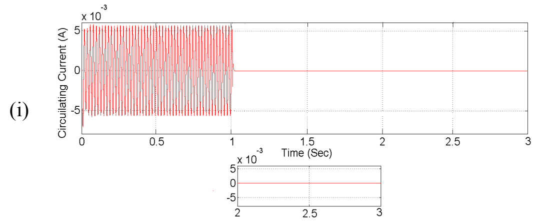


Fig. 6. Virtual impedance-based control technique results: (a) current wave form at load, (b) voltage wave, (c) MG active power, (d) active power sharing, (e) MG reactive power, (f) reactive power sharing, (g) frequency at PCC, (h) voltage at PCC, and (i) circulating current.

VI. CONCLUSION

In this paper, the virtual impedance loop was used to solve the power sharing issues of an MG without compromising the voltage quality of the system. Active and reactive power sharing accuracy can be attained very easily. Voltage drops due to the mismatch of output impedances were also minimized in this control scheme. The proposed control scheme is applied to the MG with two parallel connected inverters having different output impedances. The mismatch was covered by introducing the virtual impedance control loop. The system was tested with different load conditions and showed satisfactory results. One of the critical issues of islanded MGs with mismatch in line impedance is the production of circulating currents, something that is also addressed in this paper. The virtual impedance loop is helpful to mitigate the circulating current issues, even after the addition of extra load, the circulating current was effectively suppressed to almost zero.

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