Decentralized Virtual Impedance-based Circulating Current Suppression Control for Islanded Microgrids

Afarulrazi Abu Bakar
Department of Electrical Power Engineering
Faculty of Electrical and Electronic Engineering
University Tun Hussein Onn Malaysia
Johor, Malaysia
afarul@uthm.edu.my

Erum Pathan
Electronic Engineering Department
Quaid-e-Awam University of Engineering Science and
Technology
Nawabshah, Pakistan
erumasad79@gmail.com

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

Muhammad Ahsan Sadiq
Department of Electrical Engineering
Faculty of Engineering & Technology
University of Poonch Rawalakot
Poonch, Pakistan
engr.ahsan@upr.edu.pk

Muhammad Imran Rabani
Department of Electrical Contracting & Maintenance
XERVON
Saudia Arabia
mimranbzu@gmail.com

Sai Babu Goli
Commissioning Division-COA
Saudi Electricity Company
Saudia Arabia
saibabu27@hotmail.com

Farheen Pathan
Department of Telecommunication Engineering
Mehran University of Engineering and Technology
Jamshoro, Pakistan
engrfarheen83@gmail.com

Muammad Asad Shaikh
Protection and SAS Commission
National Grid SA
Saudi Arabia
csd_sec@yahoo.com

Abstract-Parallel connected inverters in islanded mode, are getting momentous attention due to their ability to increase the power distribution and reliability of a power system. When there are different ratings of Distributed Generation (DG) units, they will operate in parallel connection due to different output voltages, impedance mismatch, or different phase that can cause current to flow between DG units. The magnitude of this circulating current sometimes can be very large and damage the DG inverters and also cause power losses that affect power-sharing accuracy, power quality, and the efficiency of the Microgrid (MG) system. Droop control, improved droop control, and virtual impedance control techniques and modifications in the virtual impedance control technique are widely used to suppress the circulating current. However, the addition of the virtual impedance to each inverter to compensate the output impedance is resistive or inductive in nature. The resistive nature of the output impedance always causes a certain voltage drop, whereas the inductive nature of the output impedance causes phase delay for the output voltage. Both problems are addressed by the proposed control mechanism in this paper. Negative resistance, along with virtual impedance, is utilized in the proposed control strategy. The output impedance is to be maintained as inductive in nature to achieve good load sharing in droop control MGs. The simulation results validate the proposed control scheme.

Keywords-circulating current; droop control; virtual impedance; distributed generations; decentralized control

I. INTRODUCTION

In a microgrid (MG) system the i-th power electronic interface is integrated utilizing different Distributed Generations (DGs) in both islanded and grid-connected mode. Besides the many advantages of the MG system, it can also operate at a plug and play function and as bidirectional energy management system [1-3] for continuous power supply. However, there are some control issues in MGs, the islanded mode of operation in particular may have power quality and stability issues. In islanded mode, the suppression of circulating current is much needed, because it may cause instability in the system. Overheating of the system components can lead the

entire system to failure because large circulating currents flow through the inverters. The circulating current is also a significant cause of reduction of MGs' transmission efficiency. Moreover, the decentralized control mechanism of the DG inverters connected in parallel faces more circulating current issues than the centralized control mechanism [4-7]. Line impedance mismatch in parallel connected inverters is the main cause of the generation of circulating currents between the inverters and can affect power-sharing among different DGs. Voltage output inequalities between DGs connected in parallel is another cause of generation of circulating currents. Several techniques have been implemented to reduce circulating currents. A multicarrier PWM method was implemented on parallel two-level converters to suppress the circulating currents in [8]. The generation mechanism of circulating currents was studied in [9-11] and a mathematical model was established for circulating current generation.

In the islanded (stand-alone) mode of operation, droop control is widely used due to its favorable characteristics such as simplicity, good active power, and the reactive power sharing capability in multiple distribution generation systems [12]. Conventional droop control is basically designed for inductive transmission lines with primary control level [13] that do not need a communication link [14]. Meanwhile, for low voltage grids with resistive impedance characteristics, the conventional droop control is not able to provide active and reactive power-sharing [15-18]. In the presence of local loads and large line impedance, MGs face voltage deviation issues and that causes an increase in the circulating currents and power sharing issues. To fix the voltage deviation problem, the conventional droop is required to be modified [19-20]. Therefore, the mitigation of the frequency issue is done by angle droop control, while voltage regulation and power-sharing accuracy [20] use Q-U dot droop control. In order to create a suppression of the circulating current a multi-loop control mechanism for parallel-connected inverter control is needed to improve system reliability and adaptability with effective utilization of droop capability with voltage and current control mechanism [21]. Non-dominated Sorting Sine Cosine Algorithm (NSSCA) and Improved Particle Swarm Optimization control techniques were used in [22, 23] for MG control in order to enhance power quality. In the context of circulating current suppression, an impedance mismatch has been addressed through adaptive virtual impedance where the values change at every instant, inequalities are removed, and the circulating current is minimized, hence, the accuracy on power-sharing is improved [24-26]. In the presence of local loads during an abrupt change in loads, a conventional virtual impedance control strategy does not give appropriate results. Faster response to load variation can be attained by virtual complex impedance [27] to improve power-sharing accuracy. One of the methods is by having a coupling inductor to overcome the circulating current issue in the voltage source converters. Saturation of the coupled inductor may occur when the low frequency circulating current is high because the coupled inductor is sensitive to low order harmonic contents that occur due to the inequalities of the converters. The mismatch in line impedance leads the system to inaccurate power-sharing in parallel connected inverters with the same

power rating. An improved droop with voltage drops compensator with no load was suggested in [24], while a proportional resonant controller was used to ensure system stability by reducing the low frequency circulating current. A control technique for the suppression of cross circulating current based on virtual impedance control was presented in [28].

This paper presents the decentralized virtual impedance-based control technique for parallel-connected islanded MGs to suppress the circulating current. Voltage and current tracking are conducted with load changing conditions. The proposed controller responded accordingly and mitigated voltage, frequency, and power sharing accuracy errors and the circulating current was suppressed effectively. The proposed control scheme was tested to a multi DG MG system with different loads. The conventional droop control was modified and implemented with virtual impedance. Moreover, the stability of the MG system was within the permissible limits.

II. DROOP BASED CONTROL METHODS FOR CIRCUILATING CURRENT SUPPRESSION

In Figure 1, an inverter with given voltage impedance parameters: open-circuit voltage $V<\phi$, output impedance of the inverter $Z<\theta$, apparent power (S), and output current of the inverter (I), is shown.
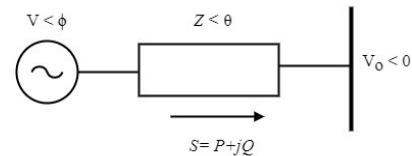

Fig. 1.   Inverter equivalent circuit.

The active and reactive powers P and Q in simplified form are taken as:

$$P = \frac{VV_o}{Z}\cos(\theta - \phi) - \frac{V_o^2}{Z}\cos\theta \quad (1)$$

$$Q = \frac{VV_o}{Z}\sin(\theta - \phi) - \frac{V_o^2}{Z}\sin\theta \quad (2)$$

Neglecting output impedance resistance, the above equations are further simplified with a same voltage phase difference, such as $\theta = 90^o$, $Z=X$, $\sin\phi=\phi$ and $\cos\phi=1$.

$$P = \frac{VV_o}{X}\phi \quad (3)$$

$$Q = \frac{V(V - V_o)}{X} \quad (4)$$

From (3) and (4) it is concluded that P and Q are dependent on phase difference ϕ and voltage magnitude difference ($V-V_o$) respectively. Subsequently, the control equations with frequency voltage droop can be given as:

$$\omega = \omega^* - mP \quad (5)$$

$$V = V^* - nQ \quad (6)$$

where ω^*, V^*, n, and m are frequency, voltage, and drop coefficients respectively.

III. VIRTUAL IMPEDANCE ANALYSIS

Droop control technique has two major flaws: a) it neglects the resistive component, which is not practically applicable and b) for double-loop control, the control parameters are affected, so the load sharing accuracy is not guaranteed. The different aspects of output impedance are given below.

A. Inverter Output Impedance

Practically, when different DG inverters are connected in parallel, the possibility to have the same parameters for each DG inverter is significantly less. The difference in the output impedance of every unit of the DG inverter causes circulating current, which needs to be suppressed. Droop control provides wireless control with virtual impedance, as shown in Figure 2. Droop characteristics and virtual impedance control technique with the transfer function of output impedance are given as:

$$Z_o = \frac{Ls^2 + (r + K_1 K_{pi} K_{PWM})s}{LCs^2 + (K_1 K_{pi} K_{PWM} C + rC)s^2 + (K_2 K_{pi} K_{PWM} K_{Pv} + 1)s + K_2 K_{pi} K_{PWM} K_{Pv}} \quad (7)$$

where K_1 and K_2 are the current and voltage co-efficients and K_{pi}, K_{pv}, and K_{PWM} are the proportion parameters and equivalent parameters respectively.

From (7), it is clear that the output impedance is influenced by the controller parameters. The virtual impedance shown in Figure 3 aims to manipulate the output impedance features.
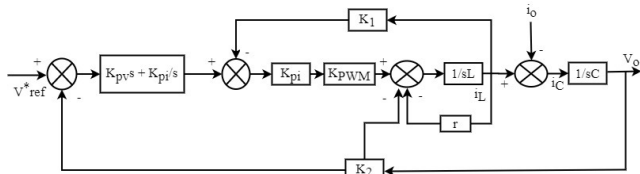

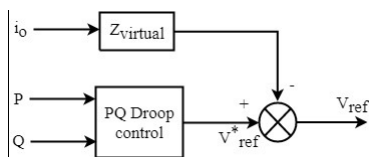Fig. 2.   Virtual impedance loop control.

Fig. 3.   Virtual impedance implementation.

B. Resistive Virtual Impedance

In Figure 4, (7) is plotted for different values of R_{vir} with the condition $Z_{vir} = R_{vir}$. The virtual impedance influences the output impedance and both are changing accordingly.

C. Inductive Virtual Impedance

Equation (7) is plotted in Figure 5 with the different values of L_{vir} for $Z_{vir} = L_{vir}$, when the values of output impedance are purely inductive. It is clearly shown that the output impedance is influenced by the virtual impedance and both are changing accordingly.
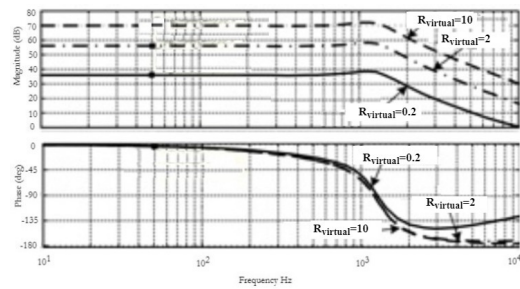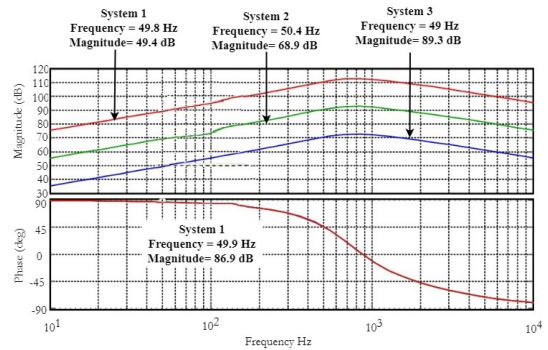

Fig. 4.   Bode plot Z_o with $R_{virtual}$.

Fig. 5.   Phase, frequency, and magnitude plot.

D. Proposed Negative Resistance Control

In parallel-connected inverter-based MGs, the mismatch in line impedance is covered by virtual impedance. The above analysis indicates that the changing virtual impedance changes the output impedance. This means that the virtual impedance characteristics are manipulated in such a way that the output impedance of the parallel-connected DG units in the MGs changed according to the demand of the load for accurate load sharing. Figures 4 and 5 illustrated that there is a massive drop in voltage amplitude and a phase delay while utilizing the resistive or inductive virtual impedance. The output impedance is changed by adding the inductive virtual impedance. The overview of the control scheme is shown in Figure 6. To analyze the output impedance, bode plots are shown in Figure 7 where the parameters for the controller are given in Table I. It is clearly shown that the addition of the virtual impedance increases the phase when it is compared with Figure 5. The change in phase is approximately from 86.96° to 89.99°, which is quite significant. It is noticed that the output impedance is purely inductive in nature after the addition of the virtual impedance. From the above analysis, it can be concluded that the improvement in active and reactive power decoupling improves the load sharing in parallel connected inverters, and the circulating current is also suppressed.
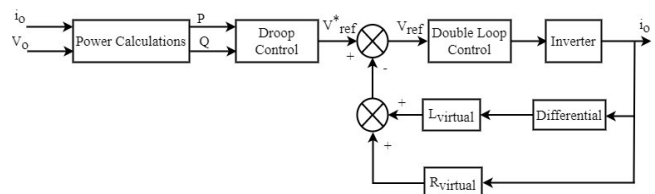

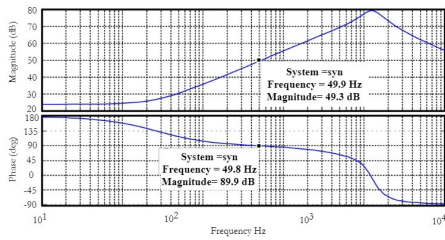Fig. 6.   Proposed virtual impedance control.

Fig. 7.   Bode plot of the proposed control technique.

IV.   SIMULATION RESULTS

The proposed control strategy was built in MATLAB/Simulink for two parallel-connected inverters with the system parameters given in Table I. The comparison between the conventional strategies and the proposed control strategy is conducted considering fixed load and sudden change in load conditions. Figure 8 shows the MATLAB/Simulink model and the sub model of the proposed control system.
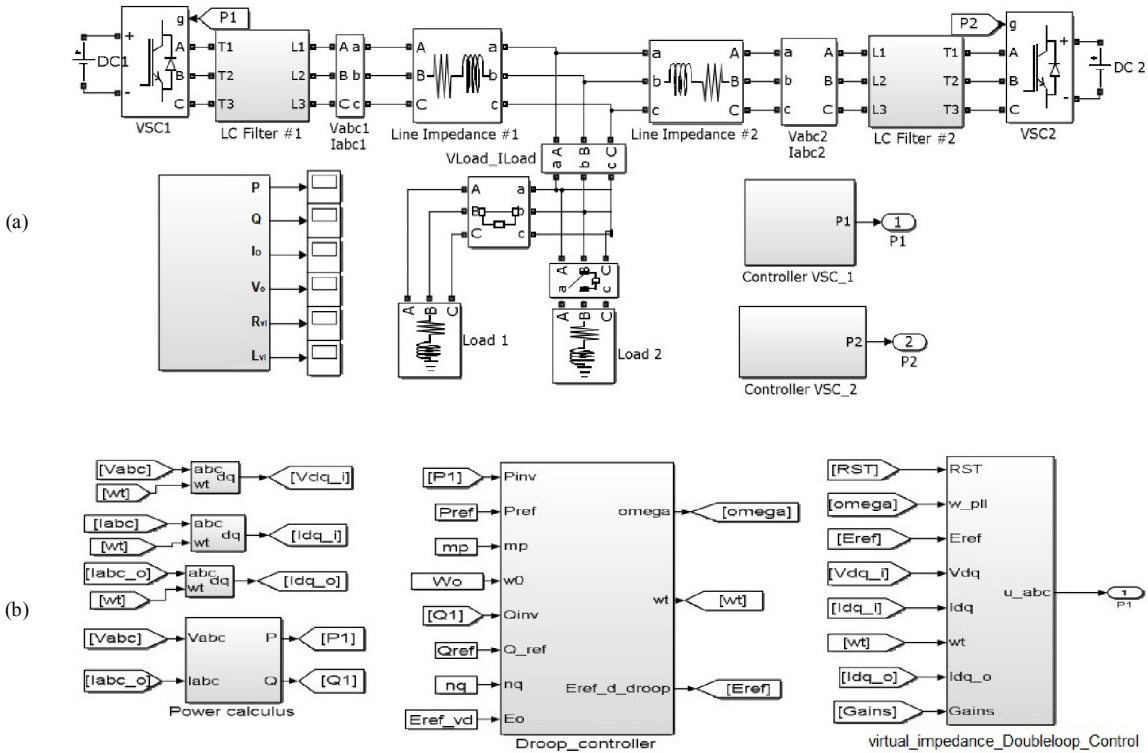

Fig. 8.   Simulation (a) two VSC-based inverters system, (b) sub-model of the proposed controller.

TABLE I.   SYSTEM PARAMETERS

Parameters	Inverter1	Inverter 2
Voltage amplitude at no load=V^* (V)	700	700
DC Bus Voltage =V_{DC} (V)	400	400
Active power=P (kW)	450	450
Reactive power=Q (kVar)	350	350
Output frequency at no load =f (Hz)	50	50
Line impedance = Z (Ω)	0.3 + j0.0002	0.167 + j0.00052
Integral parameter of voltage controller = k_{pi}	2400	2200
Inverter switching frequency = f (kHz)	20	20
Droop coefficient frequencies=m,n	$6.5*10^{-5}$, $2.2*10^{-3}$	$6.5*10^{-5}$, $2.2*10^{-3}$
Output filter capacitor = C (μF)	30	30
Output filter inductor resistance =r (Ω)	0.11	0.17

A.   Comparison in Fixed Load Conditions

The fixed load conditions are categorized in three cases:

- Case 1

At t=0.5s, conventional droop control is applied to the system, as shown in Figure 9. Circulating current, output power ratio and output power magnitude difference are shown separately for each inverter.

- Case 2

After t=1s, improved droop control is applied to the system up to t=1.5s. Circulating current, output power ratio, and output power magnitude difference are shown separately for each inverter (Figure 9).

- Case 3

From t=1.5s up to t=2s, the proposed virtual impedance control scheme is applied to the system. It is clearly shown in Figure 9 that the circulating current is not reduced initially when even there is a same voltage for each inverter. The circulating current is suppressed only when a voltage drop is recompensed by equalizing impedance mismatch in the

connected feeders. The output magnitude difference of the inverters is separately presented here. When t=0.5s, both DG inverters have the same voltage to the load connected to the system in convention droop control. The circulating current is larger and power distribution deviations are clearly observed due to the mismatch in line impedance. From t=1s, by implementing the improved droop control the errors due to line impedance mismatch are reduced and the circulating current is suppressed effectively to some extent. It is clearly shown that from t=1.5s to 2s, by implementing the virtual impedance control scheme, the mismatch of line impedance is covered efficiently, and the circulating current is suppressed. Moreover, power-sharing accuracy increased by implementing the proposed control scheme.

B. Comparison in Sudden Load Change

Implementing the proposed virtual impedance control scheme to an MG based on DG inverters connected in parallel, the circulating current is suppressed efficiently and the power sharing accuracy improves in the case of sudden load change. During the sudden load change, the conditions are the following: P=450kW and Q=350kVar. It is clearly shown that when t=0.5s the system is instable. When the power is reduced to 50% from 450kW to 225kW and from 350kVar to 175kVar for P and Q respectively, at time t=1.0s, each load is analyzed as in condition 2. In condition 3, the power is raised by 20 % as of condition 1 at time t= 1.5s. In Figure 10, it is shown that the deviation in frequency is in the allowable range and the circulating current for each inverter is less than 5% of the rated current.
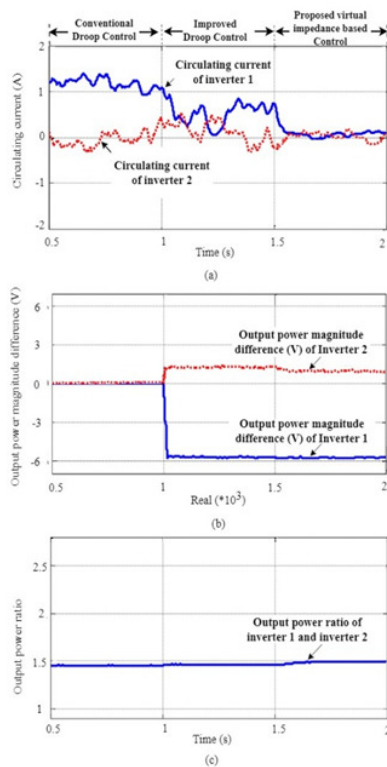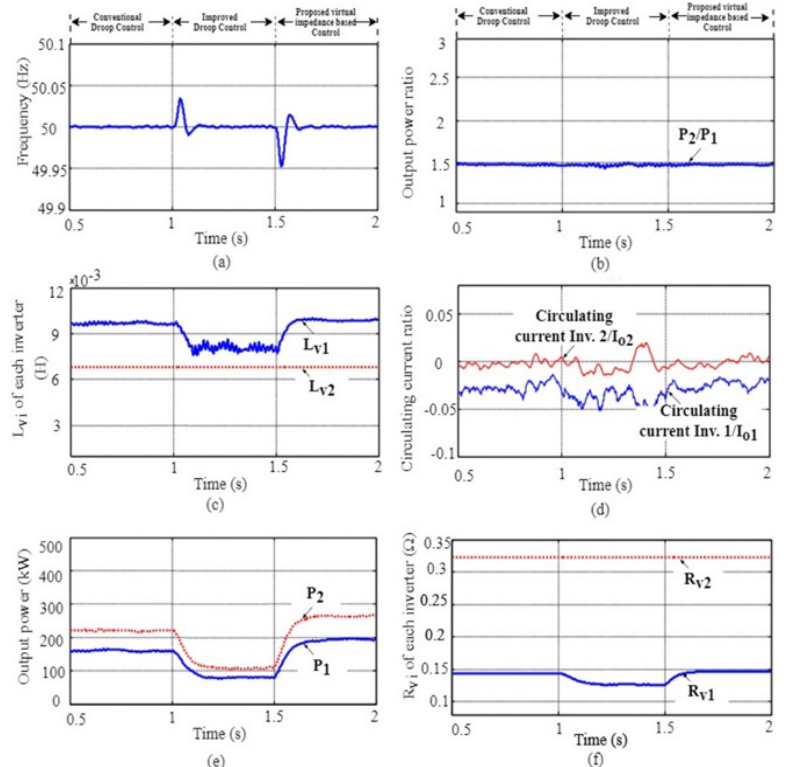
Fig. 9. Comparison of control techniques with different schemes for inverters 1 and 2: (a) circulating current, (b) magnitude difference, (c) output power ratio.

Fig. 10. Simulation results with load change for inverters 1 and 2: (a) frequency of the system, (b) output power ratio, (c) L_{vi}, (d) circulating current, (e) output power, and (f) R_{vi}.

V. CONCLUSION

A circulating current suppressed scheme that utilizes the virtual impedance along with improved droop control and negative resistance is presented in this paper. The proposed control strategy offers decentralized control, which is the most stable and reliable among control strategies. Moreover, the use of virtual impedance to equalize the output impedance of the feeders as purely inductive provides equal power-sharing according to the capacity of the inverters connected in parallel in the MG system. The simulation results indicate that the proposed decentralized virtual impedance control strategy can efficiently compensate the voltage drop of the reference voltage and suppress circulating currents. The proposed control strategy equally shares the load in the case of sudden change in connecting loads without having any significant effect on the stability of the system.

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