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A Power Sharing Method for Parallel Inverters with Virtual Synchronous Generator Control Strategy

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Abstract

A new power sharing method of a virtual sychronous generator control based inverters is introduced in this paper. Since virtual synchronous generator has virtual inertia and damping properties, it significantly enhances the grid stability. However, its output power considerably affects by the line impedance. Thus, in this paper, the relation between the droop control and the line impedance is analyzed at first. Then, by appling an improved droop control strategy to an inverter based on the virtual sychronous generator control, achieving proportional active and reactive power sharing unaffected by the line impedance is realized. The result shows that a smooth response is achieved. As well as, the voltage drop caused by the line impedance is totally compensated. As a result, the system stability is furtherly improved. At last, the effectiveness of the proposed method is verified through MATLAB/SIMULINK.

Keywords: *virtual synchronous generator, improved droop control, power sharing, different inverters capacities*

1. Introduction

More distributed generators (DGs) are being connected to power system in recent years. However, due to their adverse effects, DGs must connect to microgrid or distributed network. In a microgrid, parallel operation of DGs is essential. Several control strategies have been developed for application of parallel DGs [1-3]. Among them, droop control method has been widely used to coordinate the operation of parallel inverters. Droop strategy has the advantage of stable operation without communication line [4]. However, due to the lack of rotating inertia, virtual synchronous generator (VSG) has proposed recently as a superior replacement for the droop control in order to improve the grid stability [5].

The main idea behined the VSG is to reproduce the dynamic properties of a synchronous generator (SG) for the power electronics-based DGs, in order to inherit the advantages of a SG in stability enhancement [6-7]. In addition, The real and reactive power delivered by the VSGs connected in parallel can be automatically shared by using the droop control. however, The effectiveness of this control strategy is restricted by the line parameters [8-10]. Even in case of mainly inductive line impedance, the droop control can only guarantee balancing of active power sharing, but the reactive power sharing is still unconfirmed. In fact, the model VSG is built basically on the droop control. Therefore, it is often to face the same restriction when applying either in any grid. In a more systematic way, the lines impedance limits the droop control to achieve accurate proportional power sharing. Therefore, it is of very important to find a new method to tackle the above problem.

The main contribution of this paper is to merge the benefits of using the VSG together with an improved droop control, towards improving the VSG to be suitable for active and reactive power sharing.

2. VSG Control

A complete diagram of inverter adopting VSG control is shown in Figure 1. According to Figure 2, the actual output active and reactive power of an inverter connected to ac bus can be expressed as:

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$$P \approx \frac{E\,V\,\delta}{Z}\sin\theta + \frac{V(E-V)}{Z}\cos\theta \tag{1}$$

$$Q \approx -\frac{E\,V\,\delta}{Z}\cos\theta + \frac{V(E-V)}{Z}\sin\theta \tag{2}$$

In high voltage system the line is mainly inductive (ϴ ≈ 90˚) [11-12]. Since δ is very small, sinδ ≈ δ, cosδ ≈ 1, then equations (1) and (2) can be simplified as

$$P \approx \frac{E\,V\,\delta}{X} \approx \frac{E\,\delta}{X/V} \tag{3}$$

$$Q \approx \frac{V(E-V)}{X} \approx \frac{E-V}{X/V} \tag{4}$$

Where E is the inverter output voltage amplitude, δ is the inverter power angle, V is the voltage of point of common coupling (PCC).

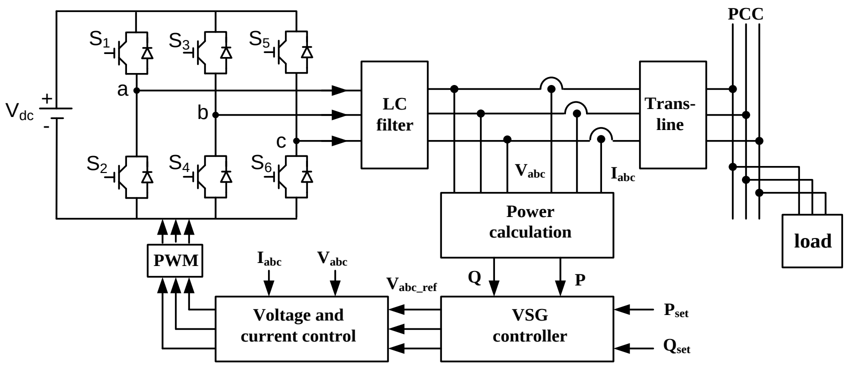


Figure 1. Inverter Connected to ac Bus

When applying Equations (5) to an inverter, it behaves like a SG. In general, equations (6) and (7) are named the traditional frequency and voltage droop control, respectively. The implementation of VSG used in this paper is shown in Figure 3. It is easy to see that, The reactive power control is totally equivalent to voltage control of the traditional droop control.

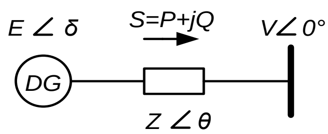


Figure 2. Equivalent Circuit of DG System Connected to ac Bus

$$J\frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega_g) \tag{5}$$

$$\omega_i = \omega_0 - m_i P_i \tag{6}$$

$$E_i = E_0 - n_i Q_i \tag{7}$$

where J is the moment of inertia, T_m is the mechanical torque, T_e is the electromagnetic torque, and D is a damping factor, E_0 reference voltage amplitude, ω is the grid frequency, ω_0 is the nominal frequency, m and n are droop parameters.

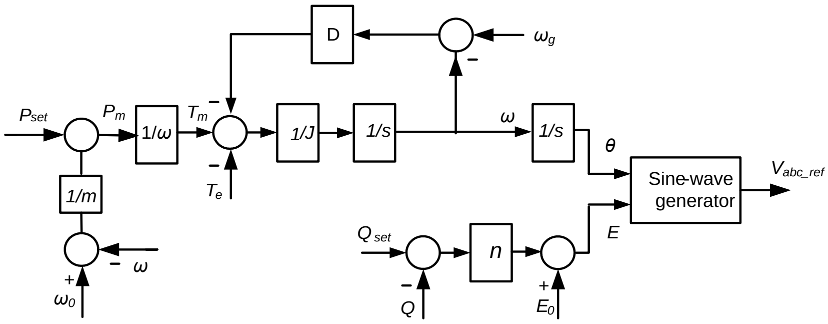


Figure 3. VSG Control Structure

3. Analysis of Traditional Droop Control Limitations

This section analysis the effect of the line impedance on the power sharing. According to Equations (6) and (7), in order for inverters to share the load in proportion to capacities, the droop coefficients should be in inverse proportion to capacities [9], [13].

$$m_1 P_1 = m_2 P_1 \quad (8)$$

$$n_1 Q_1 = n_2 Q_1 \quad (9)$$

This means, the following equations shoud be satisfied

$$\omega_1 = \omega_2 \quad (10)$$

$$E_1 = E_2 \quad (11)$$

$$\delta_1 = \delta_2 \quad (12)$$

By substituting (4) into (7), the voltage amplitude can be rewritten as

$$E \approx \frac{E_0 - V}{1 + X/nV} \quad (13)$$

Since the parallel inverters in steady state work under the same frequency, this will guarantee the active power sharing accuracy regardless of the line reactance value. However, in order for equation (9) to hold, equation (11) should be satisfied. This is only satisfied if

$$\frac{n_1}{X_1} = \frac{n_2}{X_2} \quad (14)$$

This is difficult condition because the line impedance is often uncontrollable. At last, errors will apear in the power sharing.

4. An Improved Droop Control

In order to deal with the problem of reactive power sharing, the method shown in Figure 4 has been proposed. In this method, two PI controller are added in reactive power control loop to keep the bus voltage constant and to guarantee V1 = V2, thus, ensuring proportional reactive power sharing [4]. The control block diagram is shown in Figure 4. However, this method has applied only for inverters based traditional droop control, and, its parformance has not tested with inverters based VSG control. Thus, in this paper, we realized this prospect.

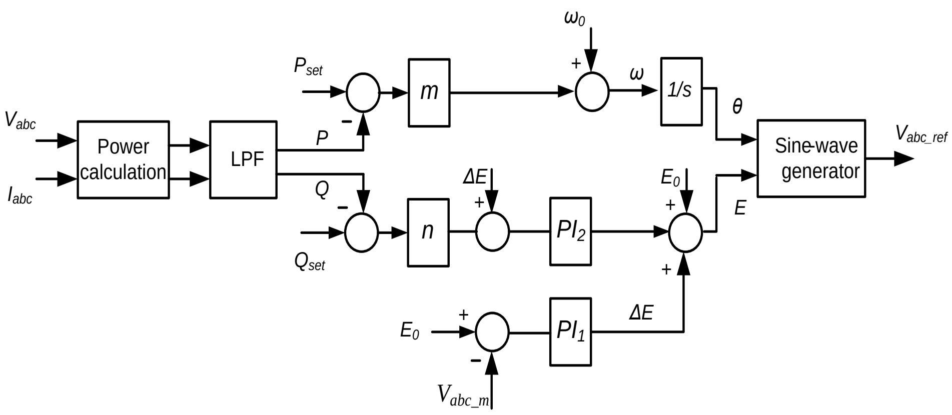


Figure 4. Improved Droop Control Structure

5. Control Structure of the Proposed Method

The VSG control method of section 2 is able to be adapted to be applicable for proportional sharing of active and reactive power in microgrid. As shown in Figure 5, the VSG swing equation and the voltage control part of the improved droop controller appear as outer loops providing the references for the inner voltage and current controllers. Quasi PR controller is adopted in the voltage loop to achieve zero steady state error [14-15]. Its structure is shown in Figure 6. Where k_r, k_p and ω_c are the proportional, resonant gains, and cut-off frequency, respectively. To verify the feasibility, matlab simulation is carried out.

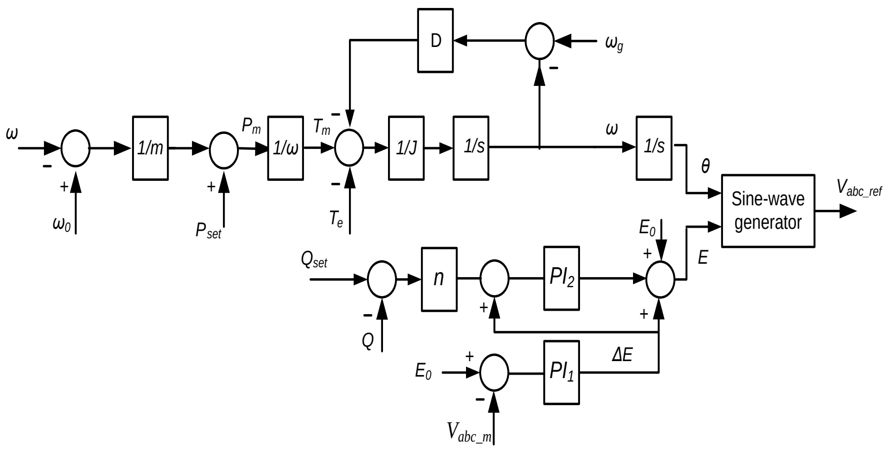


Figure 5. Overall Control Diagram of the Proposed Method

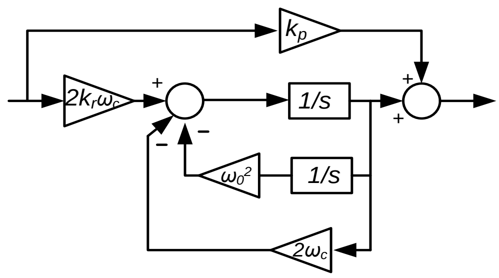


Figure 6. Quasi-PR Controller

6. Simulation Results

Figures 7 and 8 are ploted in order to clarify the built-in frequency-active power and voltage-reactive power droop mechanism of the VSG.

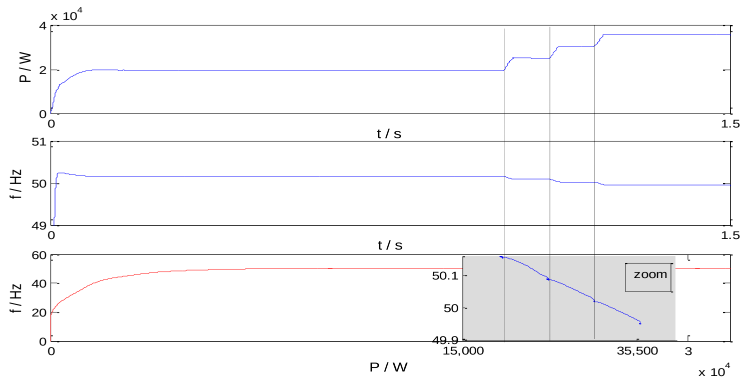


Figure 7. Frequency vs Active Power Droop Control

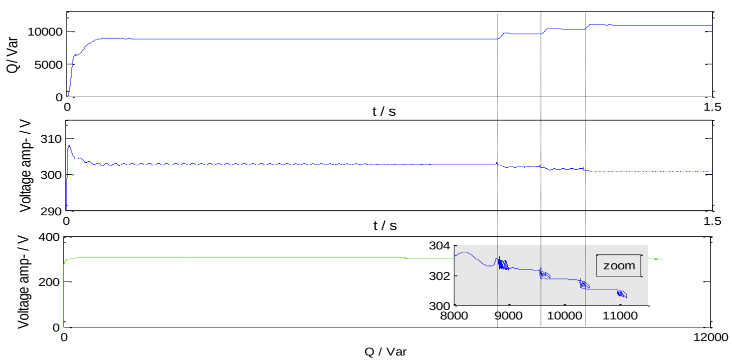


Figure 8. Voltage vs Reactive Power Droop Control

It is obvious that, When the active power demand increases, the speed of the VSG drops. Whereas, the voltage amplitude drops, when the reactive power demand increases. 10kW step loads are added at t =1, 1.1, and 1.2 second to simulate the frequency droop, while 2kVar step loads are added to generate the voltage droop.

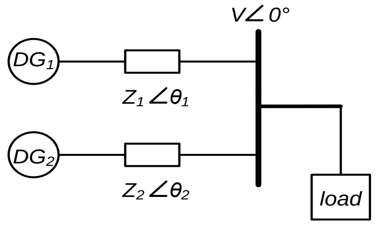


Figure 9. Equivalent Circuit of Two Inverters Connected in Parallel in Microgrid

Secondly, In order to test the new method, two inverters are connected in parallel as shown in Figure 9 to supply a load of 30kW and 1kvar through LC filters and lines in stand-alone microgrid. Assume that the capacity of inverter 2 is twice that of inverter 1. parameters of both inverters are the same, active and reactive power droop coefficients are inversely proportional to the capacities of two inverters. Parameters for simulation are shown in Table 1 and 2.

Table 1. Parameters of Parallel Inverters

Parameter	Value	Parameter	Value	Parameter	Value
V_{dc}	800V	f_s	5kHz	n_1	0.003
L	1.5mH	ω_g	314rad/s	n_2	0.0015
C	150μF	D	40pu	J	0.1kg.m^2
K_p	4	m_1	100	ω_c	3.14
K_r	100	m_2	50	E_0	311V

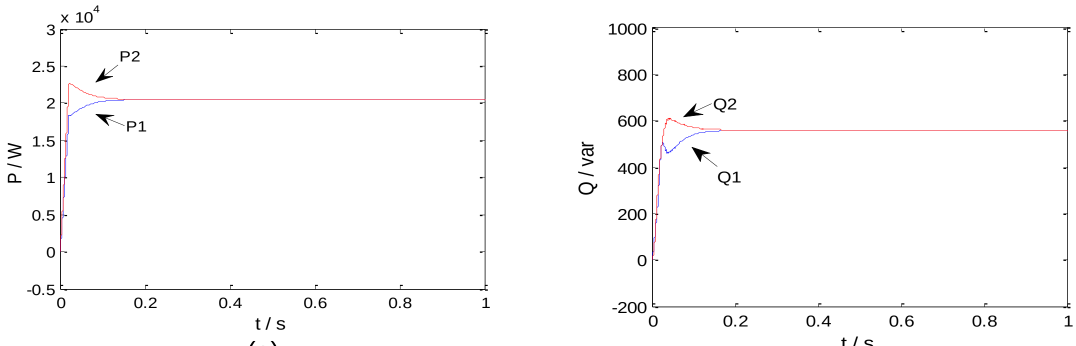
Table 2. Simulation Parameters

Case number	L_1/L_2 mH	P_{set1}/P_{set2} kW
I	1/0.5	15/15
II	1/0.5	15/30
III	0.65/0.65	15/30

Different simulation results are obtained in islanding mode of operation for:

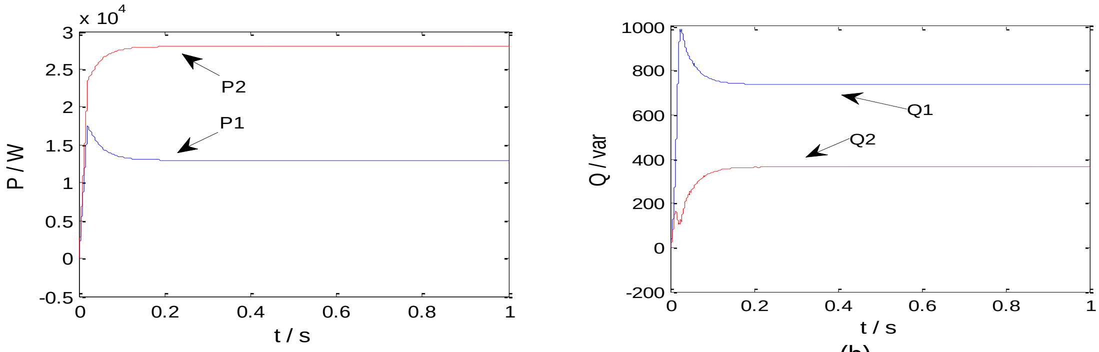
a. Same inverters capacities and different Inductive lines parameters as in Figure 10,
b. Different inverters capacities and different Inductive lines parameters as shown in Figure 11,
c. Different inverters capacities and similar Inductive lines parameters as shown in Figure 12.

The results are plotted for the active and reactive power, respectively, as shown in Figures 10-12. The resulting electrical power is shown that, the active and reactive power output of the two inverters are both proportionally shared very well. It can be also seen that, inverter with inertia and damping exhibits a smooth transient response and reaches steady state very quickly.



(a) (b)

Figure 10. Simulation Results of Case I

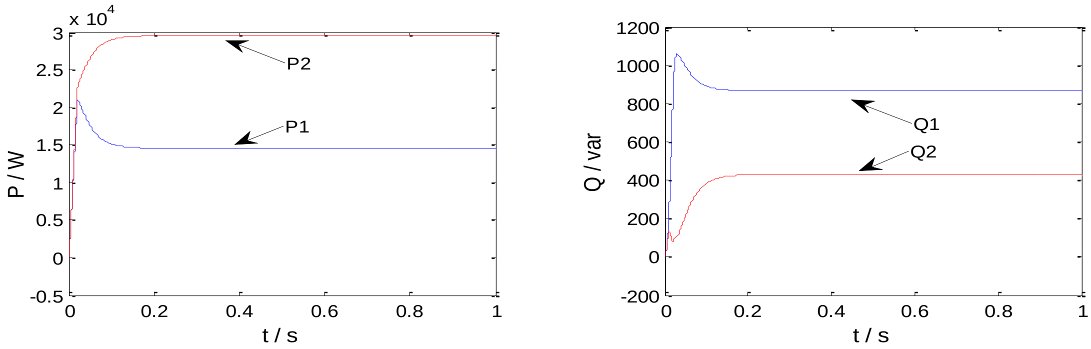


(a) (b)

Figure 11. Simulation Results of Case II

Figure 13 represents a clear picture of frequency response to inertia change. The smaller the value of inertia is, the faster the system response will be. Whereas, Figure 14 shows the impact of the damping torque on the frequency response. As conclusion, It is better to increase the damping torque to decrease the oscillation amplitude.

From Figure 8 it can be also seen that, the output voltage is lower than the set point, that because there is not a mechanism to increase the voltage set-point in the VSG applied traditional droop control scheme. Whereas, Figure 15 shows that the PCC voltage is kept constant at 220V. This means, the voltage drop caused by the line impedance is totally compensated. This result is compatible with that mentioned in section 4.



(a) (b)

Figure 12. Simulation Results of Case III

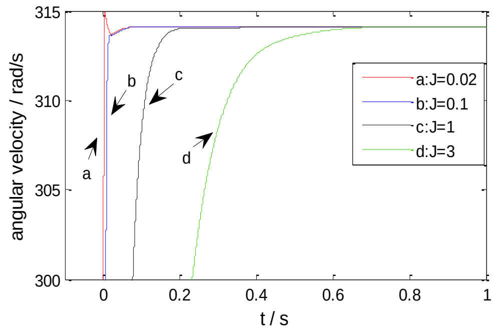


Figure 13. Frequency Response when Inertia Changes

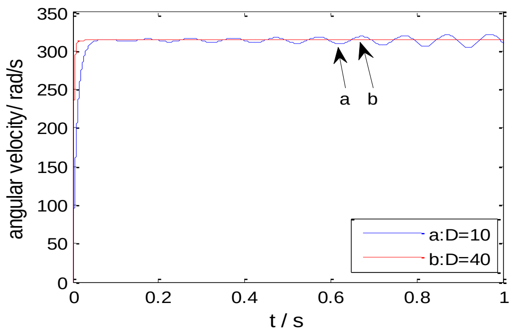


Figure 14. Frequency Response when Damping Torque Changes

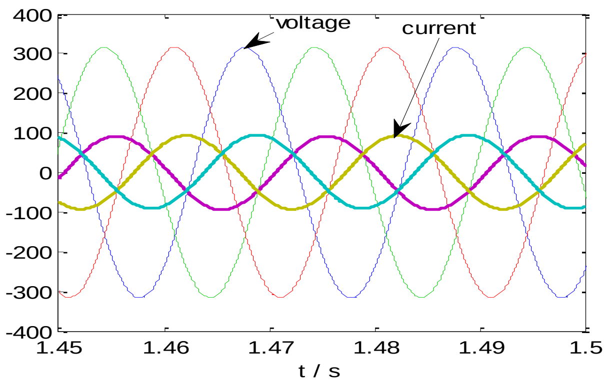


Figure 15. PCC Voltage and Current Waveforms

7. Conclusion

In this paper, some limitations of the droop control strategy are discussed. Then, the built-in droop of the VSG are plotted to verify that the frequency-active power and voltage-reactive power droop mechanism still be used.

In addition, this paper aimed to combine the benefits of the VSG control together with an improved droop control towards improving the VSG to be suitable for active and reactive power sharing in microgrid. As a result, proportional power sharing is achieved among parallel DGs applying VSG control. Excellent results are obtained for two parallel inverters forming a microgrid by using MATLAB/SIMULINK. The voltage drop of the traditional droop method is also compensated.

Acknowledgment

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