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Power Sharing for Inverters Based on Virtual Synchronous Generator Control

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Abstract

Power sharing is the most important challenging today, especially for parallel operation inverters. Recently to fixed this problem the virtual synchronous generator control strategy has been used. This paper introduced the parallel operation of three-phase multilevel inverters with different capacities to share load power by used a newly strategy named VSG with droop method controller. The control strategy is used to make the inverters to emulate the transient and dynamic charateristics of conventional synchronous generator and to gives accurate load sharing among the inverters in proportional to their ratings. To verify the performance of the proposed technique MATLAB/Simulink package for simulation experiment is established.

Keywords: *parallel operation; three phase multilevel inverter; droop controller; virtual synchronous generator control; load sharing*

1. Introduction

For the environmental effects, the distributed generators (DG) based on renewable energy sources connecting to the power system via power electronic inverter are growing [1]. This type of inverters can operate as conventional synchronous generator. Although, the 2-level inverter offers fast and accurate control of the output power, it requires a DC voltage higher than the peak AC voltage which is not always directly available, high frequencies about (3 kHz- 10 kHz) and AC filters to obtain high quality output voltage and current.Thus, it has limited used mainly due to switching losses, switching device voltage rating constrains, and high electromagnetic interference (EMI) [2]. On the other side, multilevel power inverters specially cascaded H-bridge multilevel inverter present the advantages of producing better quality waveform (low total harmonic distortion) at the point of connection to the grid and facilitating the large scale integration of DG due to their modularity [3-7].

Generally, the DG can operate in island mode or grid connected mode. In case of island mode, how to share active and reactive power among parallel connected inverter become a challenging [1]. Under islanding mode, voltage magnitude and frequency are drift at the point of common coupling (PCC) therefore islanding protection is important issues. The Islanding Detection Methods (IDMs) have been used, which classified in to three type: passive, active, and remote methods. Passive IDMs relay on the detection of the disturbance in the voltage at PCC, which are effective in preventing islanding in system with large power imbalances. Active IDMs use avariety of methods in an attempt to cause an abnormal condition (disturbance) in the PCC voltage’s magnitude and frequency [6].

There is various control methods for distribution generators have been developed. One of them used current sources inverter (CSI) control, but the drawback of this method mentioned before is that the CSIs as DGs are not able to work in an island mode, and also in case of lack of inertia cannot take a major proportion in the network [8-10]. To solve this problem the voltage sources inverters control methods are used instead of CSIs. There are several methods like droop control is a well applied for VSI control, which is used to solve the problems as islanding mode operation and power sharing. But DGs equipped with droop control are experiences some problem as the instability of frequency because of the lack of inertia. Thus, the voltage sources inverter has a new method for control have been proposed named virtual synchronous

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generator VSG. The concept of the virtual synchronous generator is to emulate the swing equation of the synchronous generator, which make the inverter like conventional synchronous generator such as dynamic characteristics, and make it have virtual inertia. the main advantages of the VSG is: the inverter output power can be made proportional to the grid frequency, by setting excitation the output voltage can be easily regulated, stability operation when more than two generator are operated in parallel, load sharing can be easily achieve by applying a frequency - active power - static etc [11]. The virtual synchronous generator (VSG) is one of the important techniques to cope with stability issues in power system when DG connected to the gird [12-14].

For parallel operation, the most important point is that the load sharing among inverters. Usually there are two types of control schemes. First one based on the communication system, which limit the system reliability, and expandability. The second one is based on droop method which operate through tight adjustment over the output voltage frequency and amplitude of the inverter to compensate the active and reactive power unbalance [15,1].

This paper introduced the parallel operation of three-phase multilevel inverters with different capacities to share load power by used a newly strategy named VSG with droop method controller. The control strategy is used to make the inverters to emulate the transient and dynamic charateristics of conventional synchronous generator and to gives accurate load sharing among the inverters in proportional to their ratings.

The rest of this paper is organized as follows: section II gives the concept of inverter description and VSG control. Mathematical model synchronous generator described in section III, in section IV the droop control for f-P and v-Q are presented, parallel operation of inverters details given in section V, in section VI simulation results and analysis are discussed, and all the simulations are performed in MATLAB/Simulink, finally conclusions are mentioned in section VIII.

2. Inverter Structure and VSG Control

Figure 1 depicts the three-phase inverter which consists of cascaded connection of 10 cells of H-bridge in each phase of the inverter. Each bridge consists of four insulated-gate bipolar transistor (IGBT) switches driven by pulse width-modulated (PWM) gate circuits, and isolated DC source. The VSC used to perform the functions of the DC/AC conversion and to interface with the grid if needed.

Figure 2 shows the power circuit for one phase leg of a three-level cascaded inverter. The circuit generates three voltages at the output (+Vdc, 0, -Vdc) as in table 1. We assume that the DC bus of the VSC is constant. Then, The AC output phase voltage is constructed by adding the voltages generated by the different cells. One advantage of this structure is that the output waveform is nearly sinusoidal [16, 17].

The overall structure as depicted in Figure3 is shown power part of the virtual synchronous generator with capacitor bank connected in parallel with the stator terminal. Figure4 depicts the electronic part (control part) of the VSG [18].

Table 1. The switching states corresponding to Figure 2

S1	S2	S3	S4	Vo
1	0	1	0	+Vdc
1	0	1	0	0
0	1	0	1	0
0	1	1	0	-Vdc

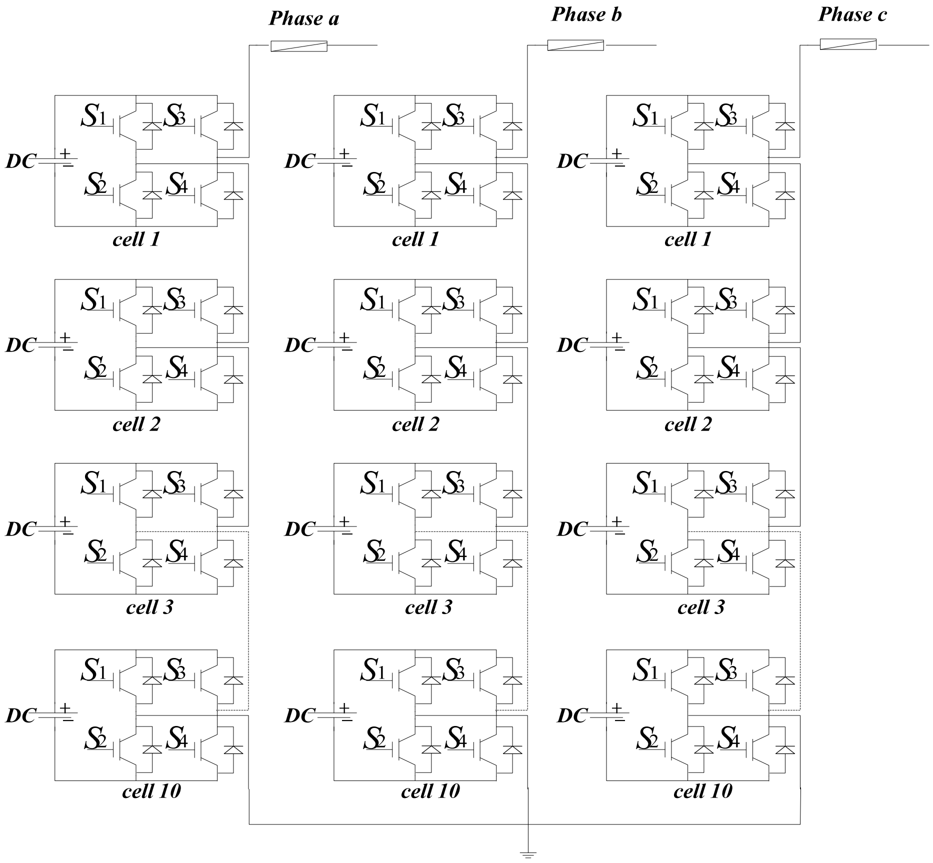


Figure 1. Three phase 21-level cascaded H-Bridge multilevel inverter (Y- connected)

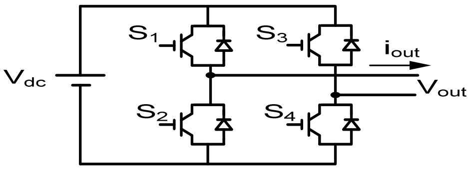


Figure 2. One cell structure of cascaded inverter

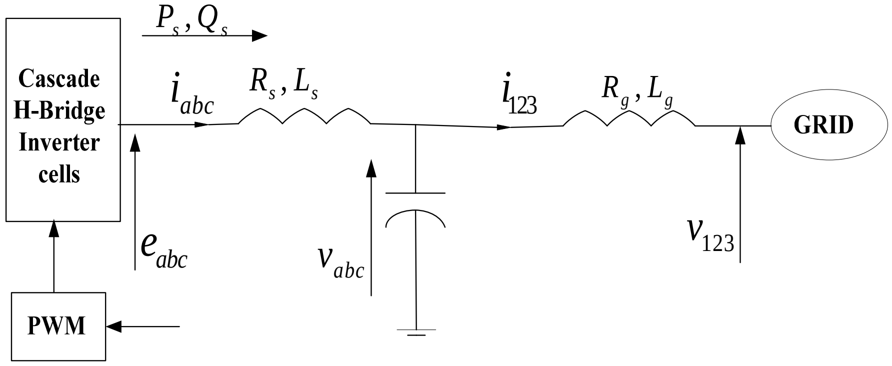


Figure 3. Power part of the virtual synchronous generator

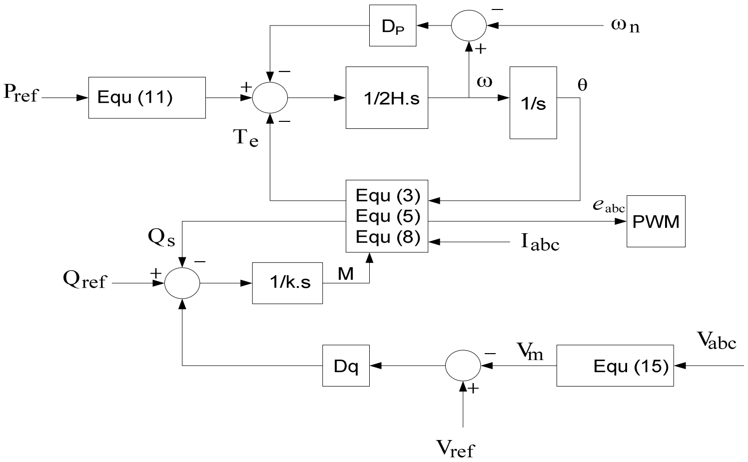


Figure 4. Electronic part (control part) of VSG

3. Synchronous Generator Mathematical Model

Figure 5 shows the simplified structure of a round rotor of the synchronous generator, which has pair of pole on the rotor part (p=1). In this paper the mathematical model that is a passive dynamic system without any assumption on the signal is established [19].

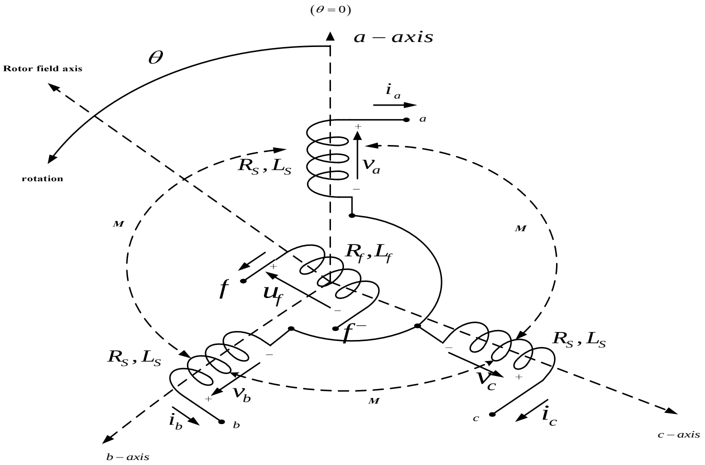


Figure 5. Structure of an idealized three-phase round-rotor SG

The mathematical model of the three-phase round-rotor SG that described by equations (1-15) is used in this paper as controller [20, 21, 17].

$$V_{abc} = -R_s i_{abc} - L_s \frac{di_{abc}}{dt} + e_{abc} \tag{1}$$

$$\left.\begin{aligned} i_{abc} &= [i_a \quad i_b \quad i_c]^T \\ e_{abc} &= [e_a \quad e_b \quad e_c]^T \\ V_{abc} &= [V_a \quad V_b \quad V_c]^T \end{aligned}\right\} \tag{2}$$

The swing equation of the synchronous machine according to mechanical part is given by:

$$2H\ddot{\theta} = T_m - T_e - D_p\dot{\theta} \tag{3}$$

$$v_{abc} = -R_S i_{abc} - L_s \frac{di_{abc}}{dt} + e_{abc} \tag{4}$$

$$T_e = M\langle i_{abc}, \widetilde{sin}(\theta)\rangle \tag{5}$$

$$e_{abc} = Ms\theta\widetilde{sin}(\theta) \tag{6}$$

$$P_s = Ms\theta\langle i_{abc}, \widetilde{sin}(\theta)\rangle \tag{7}$$

$$Q_s = -Ms\theta\langle i_{abc}, \widetilde{COS}(\theta)\rangle \tag{8}$$

$$\left.\begin{aligned} \widetilde{sin}\theta &= \begin{bmatrix} sin\,\theta & sin\left(\theta - \frac{2\pi}{3}\right) & sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}^T \\ \widetilde{cos}\theta &= \begin{bmatrix} cos\,\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}^T \end{aligned}\right\} \tag{9}$$

Where T_e is the electromagnetic torque. θ is the rotor angle. P_s and Q_s are the active and reactive power respectively.H is the inertia constant.

4. Droop Control

For emulating the droop controller of conventional synchronous generator to operate the inverters, there is very important controller required which is generating the mechanical torque signal T_m and field excitation M signals which are given as: [4]

$$T_m = T_{m\_ref} + D_p(\omega - \omega_n) \tag{10}$$

$$T_{m\_ref} = \frac{P_{ref}}{\dot{\theta}_n} \tag{11}$$

$$M = \frac{1}{KS}(Q_m - Q_s) \tag{12}$$

$$Q_m = Q_{ref} + D_q\left(v_{ref} - v_m\right) \tag{13}$$

$$T_m = T_{m\_ref} + D_p(\omega - \omega_n) \tag{14}$$

Where T_m is the mechanical torque applied to the rotor.M is the field excitation. $\dot{\theta}$ is the angular speed. ω_n is the nominal mechanical speed.D_p is the frequency droop coefficient. D_q is the voltage droop coefficient. V_m is the output voltage amplitude which is given as:

$$V_m = \frac{2}{\sqrt{3}}\sqrt{(v_a v_b + v_b v_c + v_c v_a)} \tag{15}$$

5. Parameters Design for Parallel Operation of Inverters

Many reasons are why inverters needed to operate in parallel. One of them is because of the limited availability of high current power electronic devices. Another one is that parallel-operated inverters are able to provide system redundancy and high reliability needed by critical customers. Moreover, the parallel operation of inverters also eases the difficulties in thermal management and design for high-power inverters.

The basic point for inverters operated in parallel is that how to share the load among them. This problem can be solved by using the droop control which is widely used; the advantage of this method is that no external mechanism is needed among the inverters to achieve good sharing.

Figure 6 shows two inverters operated in parallel [22, 23]. In which the output impedance is inductively ($X \gg R$).

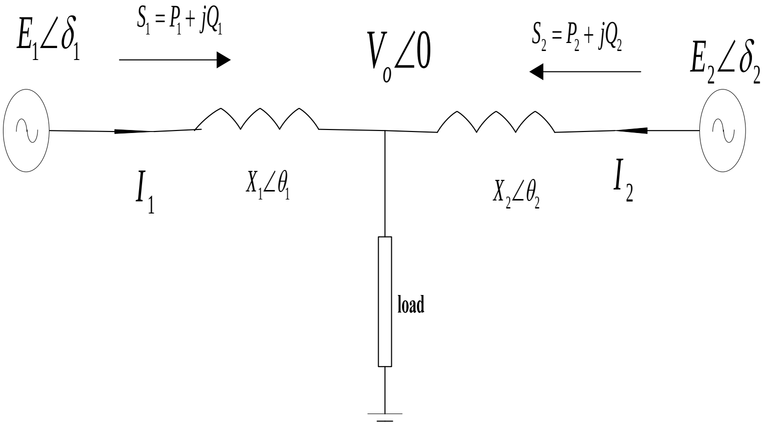


Figure 6. Two inverters operated in parallel

Generally the current following to the load source from the inverter through the impedance is given as:

$$\dot{I}_i = \frac{E_i\angle\delta_i - V_O\angle 0}{X_i\angle\theta_i} \tag{16}$$

Then the active and reactive power delivered by the inverters to the terminal are given as:

$$P_i = \left(\frac{E_iV_o}{X_i}\cos\delta_i - \frac{{V_o}^2}{X_i}\right)\cos\theta_i + \frac{E_iV_o}{X_i}\sin\delta_i\sin\theta_i \tag{17}$$

$$Q_i = \left(\frac{E_iV_o}{X_i}\cos\delta_i - \frac{{V_o}^2}{X_i}\right)\sin\theta_i - \frac{E_iV_o}{X_i}\sin\delta_i\cos\theta_i \tag{18}$$

Where

δ_i the power angle

For case of the output impedance is inductive which lead θ_i to 90° the active and reactive power are became as:

$$P_i = \frac{E_iV_o}{X_i}\sin\delta_i \text{ And } Q_i = \frac{E_iV_o}{X_i}\cos\delta_i - \frac{{V_o}^2}{X_i} \tag{19}$$

And when small δ_i

$$P_i \approx \frac{E_iV_o}{X_i}\delta_i \text{ And } Q_i \approx \frac{V_o}{X_i}E_i - \frac{{V_o}^2}{X_i} \tag{20}$$

Generally, the droop control strategy for different inverters operated in parallel with output impedance ($X \gg R$) takes the form:

$$E_i = E^* - D_{qi}Q_i \tag{21}$$

$$\omega_i = \omega^* - D_{pi} P_i \tag{22}$$

For shared load power among different capacities of inverters the output currents of inverters should be distributed in proportional to their ratings, then the following equations should be satisfied;

$$\frac{i_1}{i_2} = \frac{S_1}{S_2} = k, \frac{D_{q1}}{D_{q2}} = \frac{D_{p1}}{D_{p2}} = k \tag{23}$$

The conditions to satisfied proportional sharing are, if

$$E_1 = E_2, X_2 = kX_1, P_1 = kP_2, Q_1 = kQ_2$$

6. Simulation Results and Analysis

In this section, to verify the performance of the proposed method, three phase 21-level cascaded H-bridge inverter has been used. The system is tested under different capacities of the inverters. Table 2 shows the system parameters. As a result, the inverters behave a synchronous generator. Since, it's important for large scale inverters to share the load in proportional to their capacities to improve the system reliability and redundancy, the real and reactive power delivered by inverters connected in parallel can be automatically shared. Figures 7 to 9 show the output power for parallel inverters (S1 = 1MVA & S2 = 2MVA), load power sharing and three phase load currents sharing respectively. Figure 10 and Figure 11 depict the output three phase currents for parallel inverters 1MVA and 2MVA. When the load step at 0.6 s from 1.8MW to 3MW the system responded very fast, and the increasing load power shared by the inverters in proportional to their ratings.

Figure 12 and Figure 13 depict the inverter output line-to-line and phase voltages which are comprise 21-level and their reduced order THD. The measured output voltage THD was 1.24% for the line voltage and 4.68% for the phase voltage.

Table 2. Simulation parameters

Parameters	**Values**	**Parameters**	**Values**
V_{dc}	560 V	H1,H2	0.0005s,0.001
V_{load}(rms)	6.6 kV	K	15×10^4
P_1	1MW	R1& R2	0.01&0.02 Ω
Q_1	2kVar	L1& L2	0.5&1mH
P_2	2MW	C	10 μF
Q_2	0.5kVar	P_{load}	2.8MW
n_1	2×10^{-4}	f_{sw}	8 kHz
n_2	4×10^{-4}	f_n	50 Hz
m_1	6.6×10^{-3}	V_{ref}	5600V
m_2	3.3×10^{-3}	ω_n	314 rad/sec

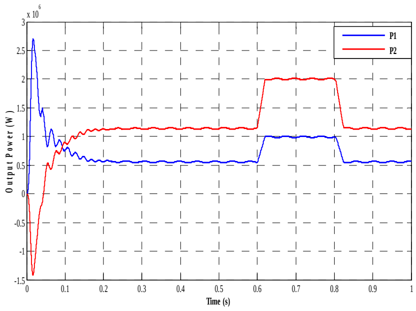


Figure 7. Output active power for two parallel inverters (P1 = 1MW, P2 = 2MW)

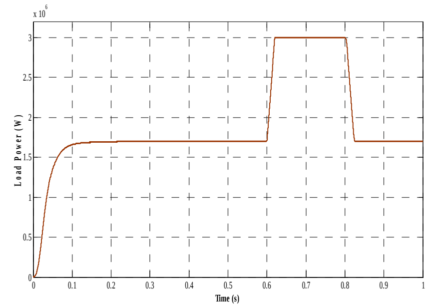


Figure 8. Active power load sharing between parallel inverters (P1 = 1MW, P2 = 2MW)

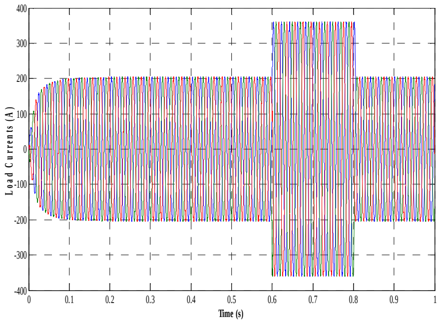


Figure 9. Three-phase load current sharing between parallel inverters (P1 = 1MW, P2 = 2MW)

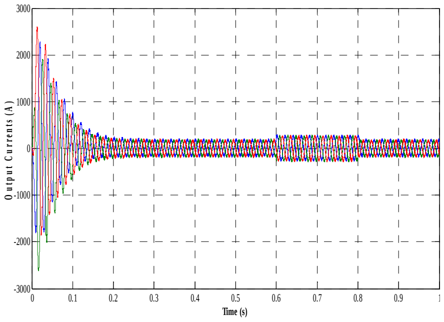


Figure 10. Three phase currents output for inverter (P = 2MW)

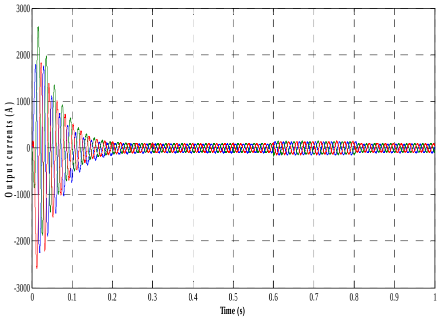
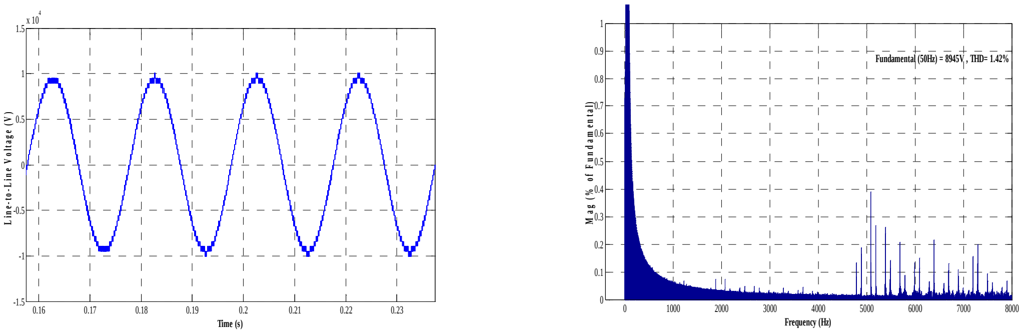
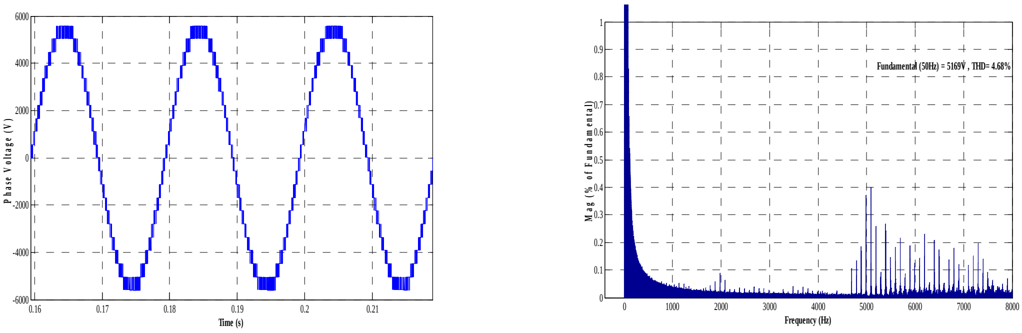


Figure 11. three phase currents output for inverter (P = 1MW)



(a) (b)

Figure 12. output for 21-level CHB inverter (a) line-to-line voltage (b) THD



(a) (b)

Figure 13. Output for 21-level CHB inverter (a) phase voltage (b) THD

7. Conclusion

This work presented share load power of different capacity of three phases parallel VSG based on multilevel inverter. The overall performance was evaluated the different capacities and different inertia constant. The proposed method was verified through simulation results. To the best of parallel power sharing to give excellent responses when operate by using the improvement and accurate droop control of medium/high voltage power system. This can open new methods applications power sharing in the future.

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