CONTROL TECHNIQUE FOR CONVERTER-CONNECTED SMALL SCALE EMBEDDED GENERATION

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Abstract - *Small-scale embedded generation (SSEG) often generate direct current (DC) that is typically converted to alternating current for practical purposes as most modern uses of electricity require alternating current (AC). This conversion usually achieved through power electronic converters. Control of these converters is needed because SSEG installations may include a mix of SSEGs interfaced via single or three-phase converters, which may give rise to voltage unbalance problems. Therefore this paper focuses on controlling the power flow from converter-connected SSEG to the load or the distribution network. Control schemes are presented which allow controlling single-phase converter and independently each phase of the three-phase converter-interfaced SSEG during grid connected or stand alone operation. These controllers technique provide additional control flexibility to balance voltages in a distribution network with high penetration of SSEGs. The performance of these controllers is tested and explained using case studies implemented in Power system simulation program (PSCAD).*

Keywords - *Small Scale Embedded Generation,* photovoltaic, voltage balance, converter control, power flow.

1. Introduction

Environmental issues and the increase of energy demand lead to looking for new energy sources near to the customer. This new energy sources generation is small-scale embedded generation (SSEG).Small-scale embedded generation (SSEG) refers to power generation under 1MVA, such as PV systems or small wind turbines which are located on residential, commercial or industrial sites where electricity is also consumed [1]. Most of the electricity generated by an SSEG is consumed directly at the site but times arise when generation exceeds consumption and typically a limited amount of power is allowed to flow in reverse - from the customer onto the utility grid [1] [2][3].Thus SSEGs would be connected to the wiring on the customer's premises which is in turn connected to, and supplied by, local distribution network. But some SSEG such as photovoltaic cells generate DC power whereas other technologies such as gas-fired micro turbines generate AC power at a frequency of a few kHz [3]. Therefore the output power from these SSEGs must be conditioned as required via power electronic converters before connecting to the system [2]. Moreover the converter controls the power exchange between the generator and the load/utility network [4]. Some controllers used in SSEG applications are based on the synchronously referenced frame and have the disadvantage that the unbalance problem is more difficult to control. This paper presents simple control strategies that permit controlling single-phase converter and in an independent way each phase of a three-phase converter-connected SSEG unit during two modes of operation stand-alone / grid connected operation. It is illustrated that this simple techniques are effective and may provide additional control capabilities to control voltage and power flow in distribution network with SSEG units. The proposed controllers have been successfully implemented and tested using a Power system simulation program PSCAD.

2. Converter for SSEG

Converter is a power electronic device that converts direct current to alternating current or alternating current with frequency different than utility frequency (50Hz/60Hz) at a voltage and frequency which enables the generator to be connected to the utility grid. For SSEG applications single or three-phase voltage source converters (VSCs) are typically used. VSCs are suitable for those applications where voltage stabilization, unity power factor operation and active filtering are required [4][5]. However some of SSEG technologies are rotating machines such as permanent magnetic synchronous generator and induction generator connected to wind turbine. The power electronic converters have very different characteristics compared to electrical machines. As an example, converter can at most inject 2 pu. of its rated current under a fault, while rotating machines can provide up to 9 p.u. of current during faults because the converter do not present the inertia feature. Moreover, converter operates as voltage source with near instantaneous and independent control of magnitude and angle in each phase [6] [7].

A. Operation Principles of Single-phase VSC

Fig.1 shows a single-phase full-bridge converter consisting of four power switches (IGBTs), with anti-parallel diodes and a DC source. By turning ON and OFF these switches in a particular manner DC is converted into AC. Two transistors should be on at the same time (g_1 and g_2) or (g_3 and g_4) for a half cycle, which can be done by using a PWM technique.

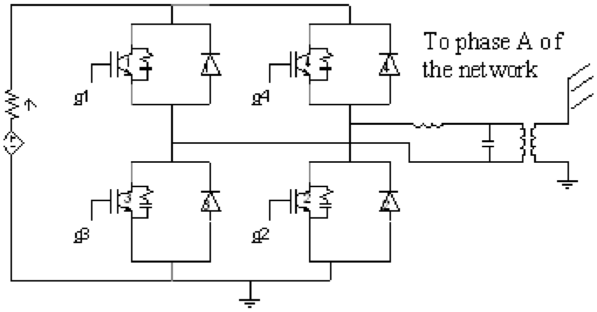


Fig. 1. Single-phase full-bridge converter connected to the distribution network.

B. Operation Principles of Three-phase VSC

A three-phase converter (Fig.) may be considered as a three single-phase converters where the output of each of these is shifted by 120º [8]. A carrier wave is compared with the reference signal corresponding to a phase to generate the gating signals for that phase.

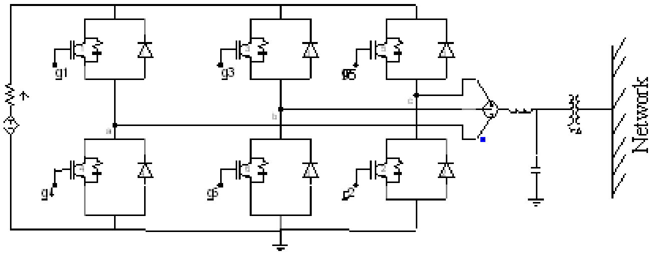


Fig.2. Three-phase converter connected to the distribution network.

3. Controller design and test for sseg during stand-alone operation

Stand-alone operation means that the SSEG is not connected to the electricity grid. Thus this section focuses on controlling the power flow from a converter-connected single source to the load. The source must supply the active and reactive power depending on load demand with suitable voltage and frequency values. In this case voltage and frequency should be kept constant; therefore a voltage and frequency (VF) control scheme was developed.

A *Basic Structure of the VF Controller*

The basic structure of the VF controller is shown in Fig. 3. The converter is controlled to maintain constant 220V and frequency 50 Hz by regulating the load terminal voltage using a PI controller. This PI controller generates the amplitude A_r for the Sinusoidal Pulse Width Modulation (SPWM.). In order to keep the frequency constant, the reference frequency of a mmmm50 Hz.

The transfer function of the PI controller is:

$$A_r(s) = \mathrm{K}_{pA}\left[1+\frac{1}{\tau_{iA}S}\right].E_V(s) \tag{1}$$

Where $E_V(s) = \left[V_{ref}(s) - V_{meas}(s) \right]$ (2)

Where V_{ref} and V_{meas} are the reference voltage and the RMS load terminal voltage respectively. K_{PA} is the proportional gain of the PI controller, τ_{iA} is the integral time constant of the PI controller that equals $\frac{K_{pA}}{K_{iA}}$, where K_{iA} is the integral gain. All the PI controllers in this work were tuned using the Ziegler –Nichols Rules [9].

B Simulation Study for a Single Source

As shown in Fig. 3 a single–phase converter interfaced small source is connected to the RL load (10 ohm and 0.00265 H). The LC (120 µF and 0.003377 H) filter is added to mitigate the fifth harmonic. The source is controlled to supply the active and reactive power demanded by the load with constant voltage of 220V and frequency of 50 Hz. The output results in Fig.4 show the source supplying the power demanded by the load and maintaining the voltage and the frequency at the pre-defined values (220V, 50Hz).

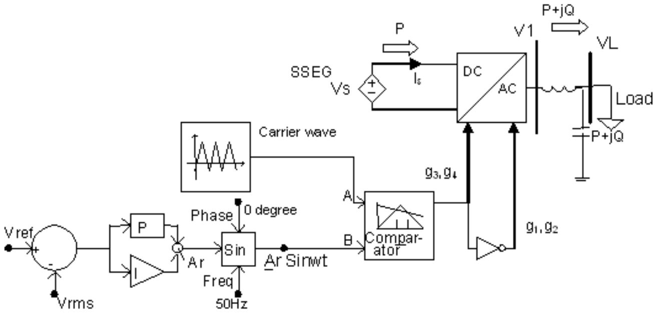


Fig. 3. Single-phase converter with the SPWM and controller

This study shows that the converter frequency can be controlled in a different way to that in rotating machine. For rotating machines there is a relationship between the speed and the frequency; in contrast, the frequency of the converter is controlled independently. Also, as shown in Fig.4 (c and d) by adding the LC filter the ideal sinusoidal waveforms of current and voltage can be measured at the load terminal.

4. SSEG during grid connected mode operation

The voltage regulation is necessary for local reliability and stability. Without local voltage and power control, systems with large number of SSEGs could experience voltage and/or reactive power oscillation. Therefore the function of this control approach that suggested in this paper is to address some of the stability issues of the system such as voltage rise and voltage imbalance issues.

4.1 SSEG controller design

The power output of the SSEG unit can be controlled by controlling the magnitude and angle of the converter output voltage. In this paper the typical power angle and voltage magnitude control method [10] is improved by adding two PI blocks, one for power angle control, and another for voltage magnitude control where power factor is used as reference value as opposed to reactive power. This is because SSEG units may be required to operate at different power factor conditions.

In addition to the proposed approach additional inductance (0.003377 H) is added between the converter and the grid connection point. This will provide some advantages such as:

- More filtering capabilities
- Reactive power control by controlling the converter output voltage
- Reduction in the difference between the resistance and inductance (as R>>X)

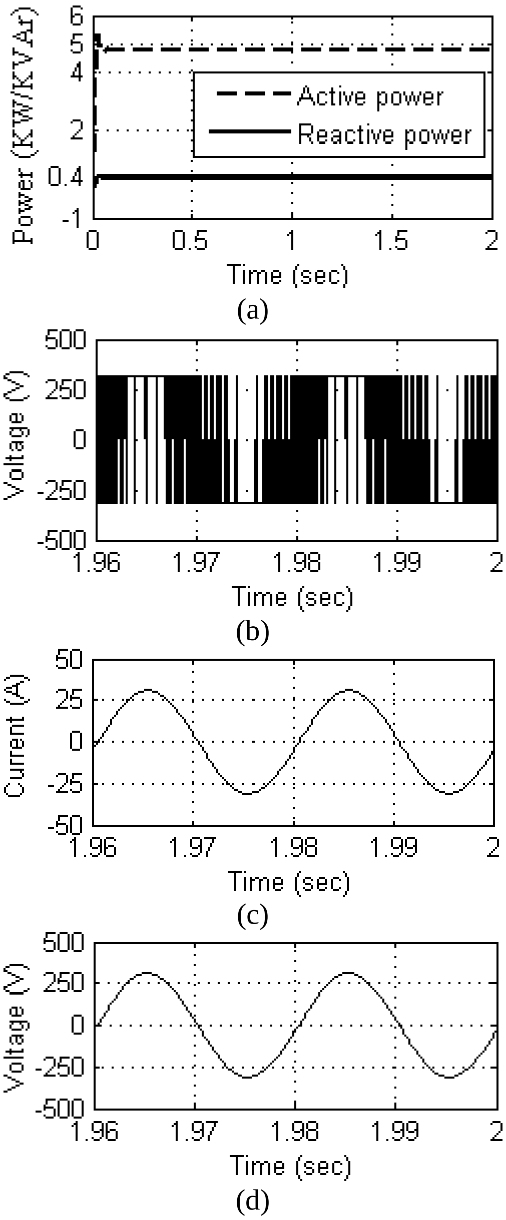


Fig. 4. Single source with no connection to the grid: (a) Active power and reactive power, (b) PWM Voltage, before LC filter (c) Current and (d) Voltage at load.

A. *Single-phase controller design*

Fig. Fig. 5 illustrates the block diagram of the proposed control of active power and power factor in a single-phase converter-interfaced SSEG.

The dynamic performance of the power angle control method can be improved by including additional PI control blocks. The power angle control technique is based on the steady-state relationships given by Eqs.(2) and (3) [11]. The magnitude of the converter output voltage relative to the grid voltage is manipulated to control reactive power flow. The active power flow is controlled by adjusting the power angle δ_p .

$$P = \frac{V_0 V_1 \sin\delta_p}{X} \tag{3}$$

$$Q = \frac{\left(V_1^2 - V_0 V_1 \cos\delta_p\right)}{X} \tag{4}$$

where

P : active power; Q : reactive power

V_1: grid bus voltage; V_0: converter terminal AC voltage

δ_1: power angle of V_1; δ_0: power angle of V_0

X : interconnecting reactance; δ_p : angle difference between V_0 and V_1

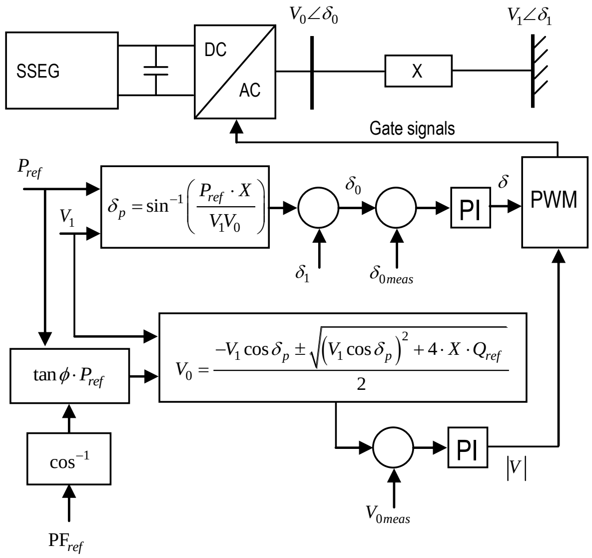


Fig. 5. Control of active power and power factor for a single phase converter.

From Eqs. (3) and (4), if $\delta_p = 0$ then the active power flow is zero, and the reactive power is determined by the magnitudes of V_0 and V_1. If $V_0 = V_1$ with $\delta_p \neq 0$, then the active power flow is determined by the angle δ_p and the reactive power flow is zero.

The load angle δ_p and the converter AC voltage are calculated as:

$$\delta_p = \sin^{-1}\left(\frac{P_{ref}\cdot X}{V_1 V_0}\right) \tag{5}$$

$$V_0 = \frac{-V_1\cos\delta_p \pm \sqrt{\left(V_1\cos\delta_p\right)^2 + 4\cdot X\cdot Q_{ref}}}{2} \tag{6}$$

where P_{ref} is the reference value of the active power that needs to be transferred from the converter to the grid, and Q_{ref} is the reference value for the reactive power. Two PI control blocks are added to track the difference between the power angle and voltage reference values and their measured values.

The maximum and minimum reactive powers depend on the power factor limitation to enhance the efficiency and stability of the system. Minimum reactive power, $Q_{\min}$, represents the minimum value the SSEG has when operating at lagging power factor. Maximum reactive power, $Q_{\max}$, represents the maximum value the SSEG has when operating at leading power factor. The maximum value of voltage, $V_{\max}$, is required when the SSEG operates at a threshold value of leading power factor. The minimum value of voltage, $V_{\min}$, is required when the SSEG operates at a threshold value of lagging power factor. These values are given by:

$$V_{\max} = \frac{V_1 \pm \sqrt{\left(V_1\right)^2 + 4\cdot X\cdot Q_{\max}}}{2} \tag{7}$$

$$V_{\min} = \frac{V_1 \pm \sqrt{\left(V_1\right)^2 + 4\cdot X\cdot Q_{\min}}}{2} \tag{8}$$

$$Q_{\max} = \frac{\left(V_{\max}^2 - V_{\max}V_1\right)}{X} \tag{9}$$

$$Q_{\min} = \frac{\left(V_{\min}^2 - V_{\min}V_1\right)}{X} \tag{10}$$

B. Three-phase controller design

For a SSEG interface through a three-phase converter this controller takes the form shown in Fig. 6 which enables independent control of each phase of the converter. A second order LC filter is used for filtering the PWM switching harmonics of the converter. The LC filter used in this work is tuned to mitigate the third harmonic. The values used are C=30 μF and L=0.03753 H. Furthermore in three phase inverter the filter is used to mitigate the fifth harmonic and in single phase inverter the filter is used to mitigate the third harmonic. Also the values of inductance in two cases are same the difference is in the value of the capacitors.

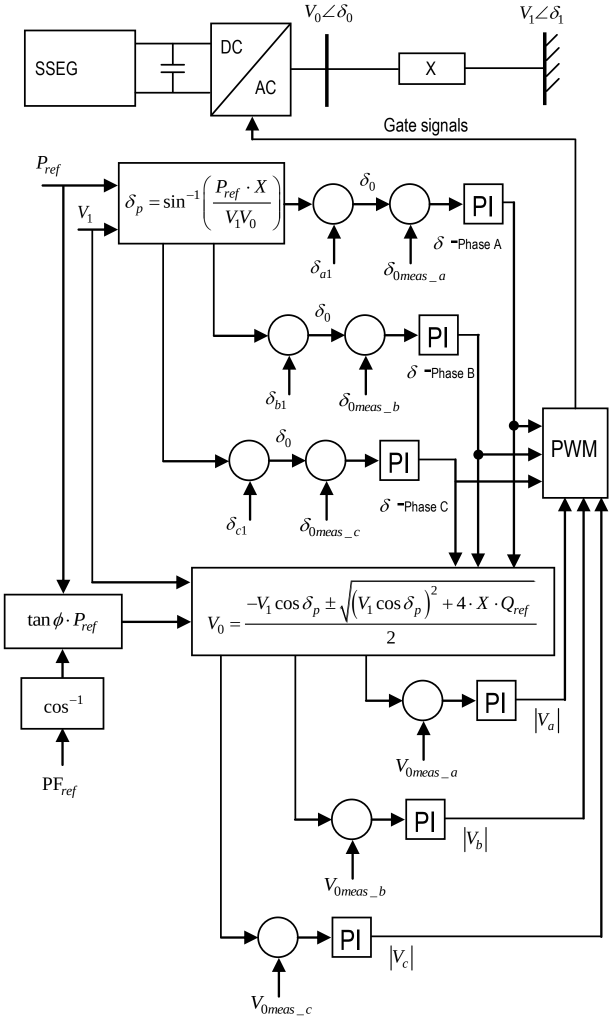


Fig. 6. Control of active power and power factor for a three-phase converter.

5. Network used in the analysis

Fig.7 shows the configuration of the distribution network used in the analysis. The electrical system is radial with two feeders A and B. The voltage level at the loads is 0.433kV. Feeder A consists of a SSEG providing heat and power to 20 local residential consumers. Feeder B provides power to 46 local residential consumers. The system is connected to the main distribution system through a transformer and a circuit breaker CB1. It is assumed that the fault level at the 11 kV main distribution network is 25 MVA, with an X/R ratio of 15. One transformer (500 kVA, 11/0.433 kV) is installed at the substation between the main network and the 0.4 kV busbar. The impedance of the transformer is 0.03326+j0.0499 p.u. The feeder A is connected to a microgenerator and load (2x10 customers) through 150 meters of 95 mm2 CNE cable. The impedance of the cable is 0.32 + j0.075 ohm/km (per phase). The load is a fixed PQ load with capacity of 28.5 kW and 9.3675 kVAr (1.5 kVA per customer). The feeder B is connected to the load (46 customers) through 150 meters of 95 mm2 CNE cable. The impedance of the cable is 0.32 + j0.075 ohm/km (per phase). The load is represented by a fixed PQ load with capacity of 65.55 kW, 21.54524 kVAr and power factor 0.95 (1.5 KVA per customer) [12].

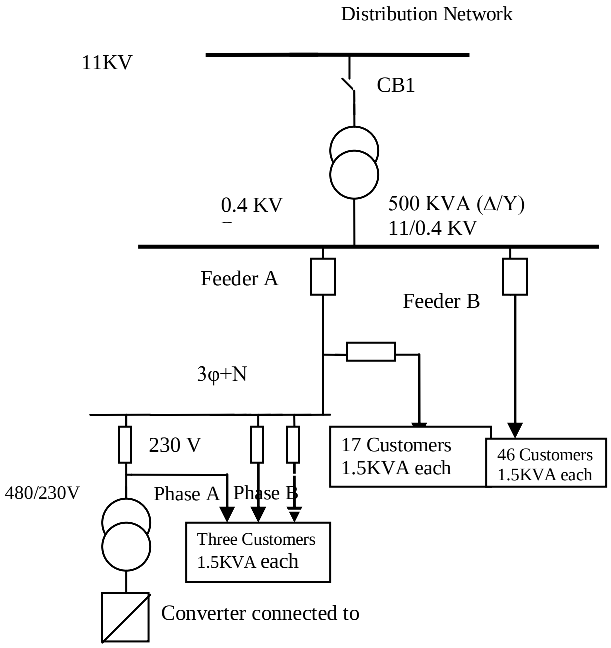


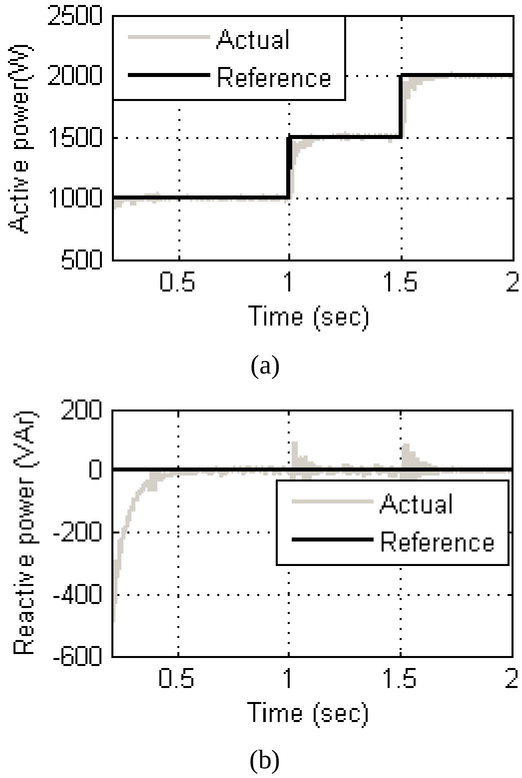
Fig. 7. Distribution network used for the studies of SSEGs connected to the network through single-phase converters.

6. Simulation results

A. *Single-phase converter-connected SSEG*

The study was conducted with a single–phase converter connected to the network of Fig.7. The capacity of the converter is 2kW (connected to one customer). The rated active power P is 2kW, rated AC voltage is 250Vrms, rated unity power factor and the power angle at full rating is 20 degrees. The converter is fed by a DC bus voltage source of 370V. The size of the inductance X is calculated from the choice that the power angle at full power output is about 20 degrees. This choice guarantees operation in the linear region of the sinusoidal characteristic. The single-phase converter is connected to the network through a transformer 4380/230 V) for isolation purpose.

The performance of the controller is tested by changing the active power set point with unity power (zero reactive power). As shown in Fig. 8the output active and reactive powers from the single phase converter follow the reference values to response to step change in demand.



(a)

(b)

Fig. 8. Response of active and reactive powers to step-changes in active power demand.at unity power factor.

B. Three-phase converter-connected SSEG

The study was conducted with three–phase inverter connected to the network of Fig.9. The capacity of the inverter is 11kVA (connected to commercial load 11kVA). Rated active power P =10kW, rated AC voltage 433V, rated power factor PF = 0.95 and power angle at full rating is 5.77 degrees. From this data it is possible to calculate every other quantity of interest. The inverter is fed by a DC bus voltage source of 860 V. The size of the inductance X is calculated from the choice that the power angle at full power output is about 5.77 degrees. This choice guarantees operation in the linear region of the sinusoidal characteristic.

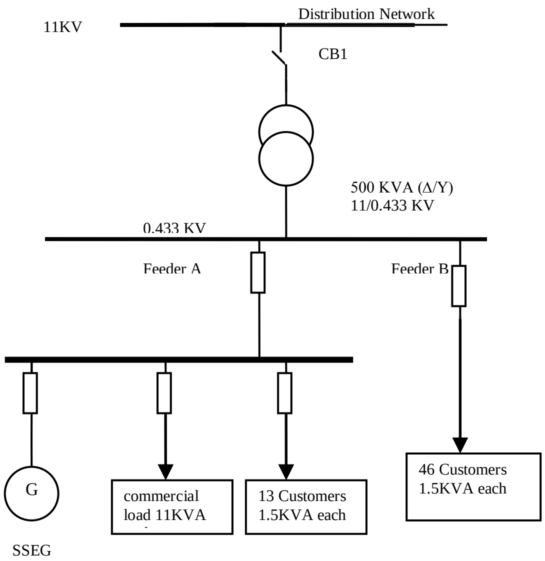


Fig. 9. Distribution network used for the studies of SSEGs connected to the network through three-phase converters.

1) Performance of controller different demand power among phases

As shown in Fig.10 the desired power from phase A is 3.33kW, from phase B is 2.4kW and from phase C is 1.5kW all working at PF=0.909. It is observed that the performance of the controller is correct with minimized steady state error and no overshoot.

As shown in Fig.11 the reactive power for every phase is different in order to maintain the power factor of all three phase at desired value, PF=0.909. The controller sends the appropriate signals to the PWM generator to adjust the modulation index of every phase depending on the desired power factor .Thus, by using this control approach the voltage imbalance problem may be solved, due to every phase can be controlled independently as shown in Fig.12. Also as illustrated in Fig.13 the sinusoidal phase currents present different amplitudes.

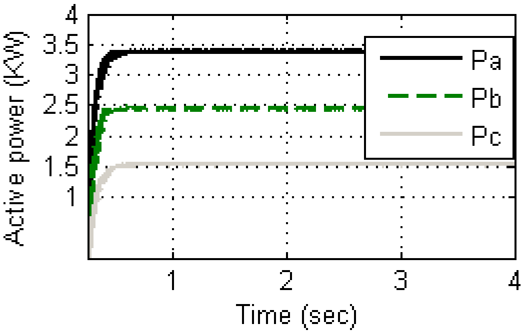


Fig. 10. Performance of active power control with different power references among phases.

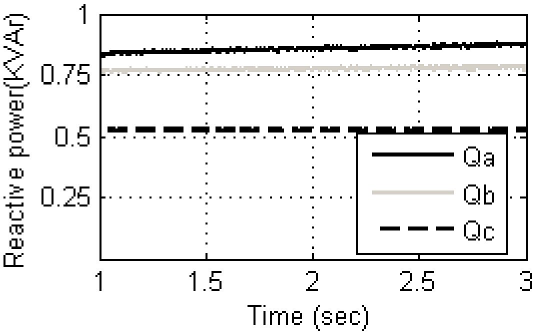


Fig. 11 :Reactive power output of the three-phase converter.

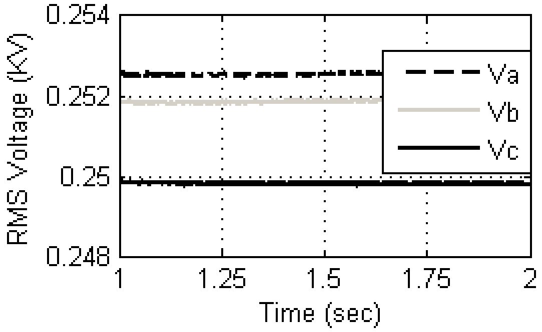


Fig.12.Three-phase converter output voltage at the desired power factor.

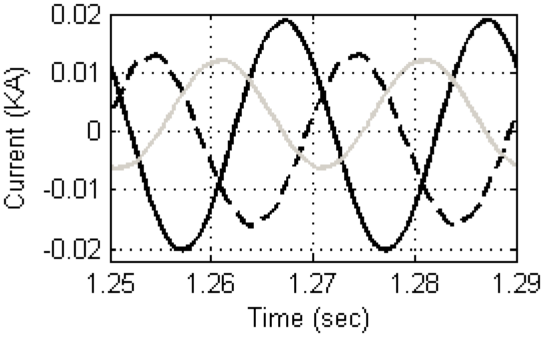


Fig.13.Three-phase converter output currents at the desired power factor.

2) Performance of controller to step-changes in demand

At time 1.75 sec the desired power from phase B is changed from 2.4 kW to 3.33 kW. Also the desired power from phase C is changed from 1.5 kW to 3.33 kW. As shown in Fig.14 the output active power of every phase follows the desired values. The SSEG operates at PF=0.909 lag.

As shown in Fig.15 and Fig.16 the controller changed the terminal phase voltages due to the change in desired reactive power. This is because the controller is designed to maintain fixed power factor in every phase. Before 1.75 sec the three phase voltages are unbalanced when the control operates after 1.75 sec with same reference value for voltage and power factor for the three phases the results show the voltages are balance.

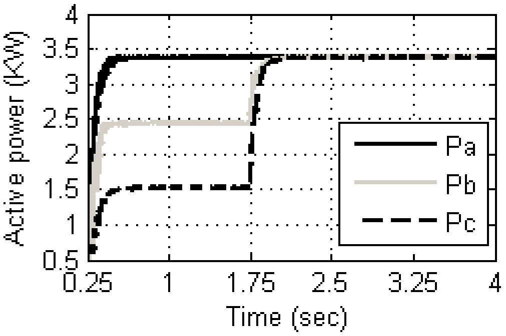


Fig. 14. Active power response in the three phases to step-changes in demand.

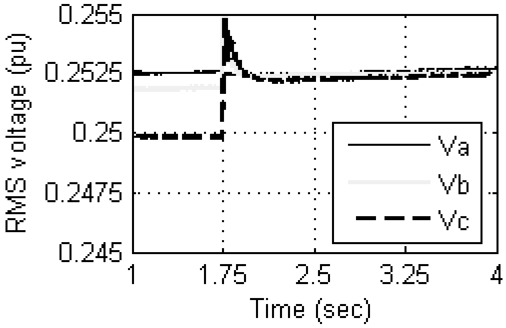


Fig. 15. Three-phase RMS output voltages.

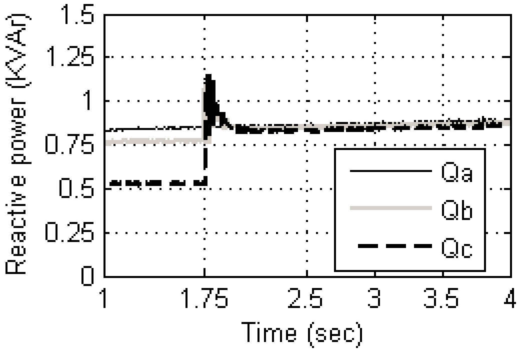


Fig. 16.Reactive power responses in the three phases to a step-change in demand.

The quality of the inverter output waveform is defined by the total harmonic distortion (THD). The total harmonic distortion (THD) is the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage[13]:

$$\text{THD}=\frac{\sqrt{V_2^2+V_3{}^2+....+V_n^2}}{V1} \qquad (11)$$

As shown in Fig.17 three phase currents are sinusoidal and have low harmonic distortion: THD=(phase A=0.267%, phase B=0.324% and phase C=0.46%).

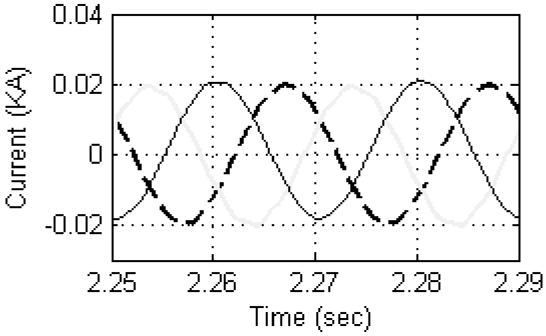


Fig.17. Three-phase converter output currents.

7. Conclusions

The main task of this paper was to propose control schemes to control output power from a converter interfaced SSEGs during stand alone operation and grid connected mode. Two types of simulation models in PSCAD were done. The first type is the converter-interfaced SSEG connected to the load as stand-alone operation and the second type is converter (single-phase and three-phase)-interfaced SSEG connected to a low-voltage distribution network as grid connected mode. The performance of the proposed controllers is tested under different load conditions. These conditions are when the active power set point is changed at unity power factor, during different demand power among phases and during step-changes in demand. The study showed that the response of the SSEG controllers was satisfactory during load changes. It was also showed that each phase of a three-phase converter can be controlled independently in order to address voltage imbalance problems encountered in SSEG applications which use single and three-phase converters to interface SSEGs. Moreover during stand alone operation the function of the controller is to control the output voltage and the frequency from the source.

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