Power Quality Assessment in Electrical Utilities Including Distributed Generation Unit & Hybrid Filters under Non-Ideal Source Voltage

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Abstract

This paper deals with a hybrid compensation system in electrical utility including a distributed generation (DG) unit under non-ideal source voltages condition. The DG unit consists of a Solid Oxide Fuel Cell (SOFC) as active power source and a three-phase full-bridge DC-AC inverter for power conversion. DG unit is controlled to deliver balanced and sinusoidal current in phase with fundamental positive sequence of source voltage with a new control strategy. The hybrid filter consists of a passive filter (PF) that is connected in series with load and a parallel active filter (PAF). The PF is tuned at fundamental frequency so it eliminates load harmonic currents. Finally PAF compensates for load unbalances and reactive power. Each of the mentioned parts will be described separately and also the system operation will be verified under unbalance and harmonic polluted source condition. The proposed system is simulated using Matlab software. The simulation results show that the proposed system has the satisfying operation.

1. Introduction

An increasing number of nonlinear and/or unbalance loads inject high amount of harmonic currents to the electrical utility which decrease the power quality. Distorted current causes additional losses in power cables and transformers; also sensitive load may be disturbed or even damaged due to harmonic voltage distortion [1]. The situation becomes more serious by the development of the distributed generation (DG) in which power electronic converters are often used to interface the generation unit such as wind turbine, fuel cell (FC), photo voltaic (PV), etc. The voltage quality problems would have the following effects on DG inverters:

1- Unbalance voltage causes unbalance current drawn from the electrical utility and DG that can deteriorate DG inverter operating margin.
2- Oscillating active and reactive power are appeared in DG output power.

Therefore, an effective compensation system is required to maintain the power quality. First DG inverter should be controlled in such a way that it would deliver balanced and sinusoidal current into the utility under all scenarios of utility voltage and second a proper power quality compensator should be placed for electrical utility to suppress harmonic currents and compensate unbalances and reactive power. Hybrid filters that are the combination of active and passive filters have been proposed in many literatures as an effective solution to overcome power quality problems [2]-[3]. Also a review of several structures of the hybrid filters was done in [4]. Concerning the control methods of the DG inverters and active part of the hybrid filters under voltage unbalances and/or distortion, several methods were investigated in literatures [5]-[9]. In [5],[6], dual current regulators, one for the positive sequence and the other for negative sequence, were used. References [7],[8] used a proportional gain plus resonant current controller in rotating frame for controlling multiple harmonics in three-phase grid converter systems and active power filters during grid voltage unbalances. In [9] a multi-frequency proportional resonant current controller in the stationary frame was proposed for grid connected converters under unbalanced supply conditions. Concerning AF control, the IRP theory introduced by Akagi, has been used very successfully to design and control of the active filter for 3-phase systems [10]. Other control methods for AFs operation during distorted utility voltage, include synchronous reference frame (SRF) [11], unity power factor (UPF) strategy [12] and perfect harmonic cancellation (PHC) strategy [13]. In [14] a new structure and control method for hybrid filters for power quality enhancement under simultaneous distortion of source and load were proposed. The hybrid filter was composed of PFs tuned at 5th and 7th harmonic frequency that were placed in series with nonlinear/unbalanced load and a parallel active filter. The PFs remove their specified harmonic currents whereas active filter compensates for residues harmonic of load, reactive power and unbalances. A Hybrid compensation system for power quality improvement in DG systems was proposed in [15]. The system is composed of two DG units, parallel distributed PFs adjacent the installation of DG units, nonlinear loads and an AF.

In this paper a new hybrid compensation system is proposed for electrical utilities with a DG unit under unbalance voltage condition. The DG unit consists of a Solid Oxide Fuel Cell (SOFC) as active power source and a three-phase full-bridge DC-AC inverter for power conversion. The DG unit is controlled to deliver balanced and sinusoidal current in phase with positive component of source voltage. The control method utilizes a new control method based on PHC strategy for current reference generation of DG inverter and a proportional resonant controller for reference signal tracking. The hybrid filter consists of a PF that is connected in series with load and a PAF. The PFs are tuned at fundamental frequency so that eliminates load harmonic currents. Finally AF compensates for load unbalances and reactive power. Then sinusoidal and balanced currents in-phase with fundamental psitive sequence of source voltage are drawn from utility. The proposed system is simulated using Power Simulink Blockset (PSB) of Matlab software and simulation results show its satisfying operation under non-ideal source voltage conditions.

2. System configuration

The single line configuration of the studied system is shown in Fig. 1. DG unit is connected in parallel with the utility and load via a three-arm three-phase PWM inverter. A three phase band pass passive filter tuned at fundamental frequency is placed in series with three phase unbalance load and compensates harmonic currents of load. The active filter is located at the upstream position to remove the remaining harmonics, to correct the unbalance of system and to compensate reactive power.

3. System control

System control is divided in to two stages. The first one relates to the control of DG unit and the second part includes hybrid filter control.

A. DG Unit Control Strategy

As mentioned earlier, DG unit consists of SOFC as power source and a three-phase three-arm PWM inverter. At first SOFC DC output voltage is fed to a boost converter and then the boosted voltage is delivered to DC link of PWM inverter as shown in Fig. 2. Dynamic equations and control block diagram of SOFC were investigated in [16]. Concerning the control of DG inverter under unbalanced voltage, it is advantageous to investigate its output power. Under such condition three-phase DG inverter output voltage can be written using symmetrical components method. Thus we have:

$$\begin{aligned} u_a &= u_{ap} + u_{an} + u_{az} \\ u_b &= u_{bp} + u_{bn} + u_{bz} \\ u_c &= u_{cp} + u_{cn} + u_{cz} \end{aligned} \tag{1}$$

in which:

$$\begin{bmatrix} u_{ap} \\ u_{an} \\ u_{az} \end{bmatrix} = \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad \& \quad a = e^{j\frac{2\pi}{3}} \tag{2}$$

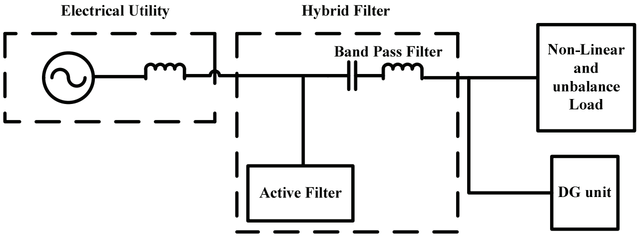

Fig.1. Single line schematic of the studied system

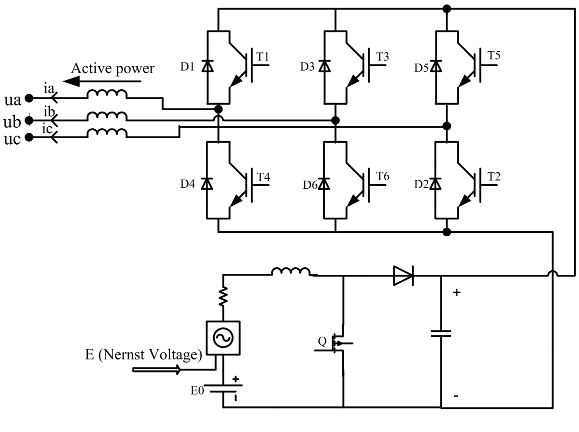

Fig.2. Single line schematic of the studied system

Knowing that zero sequence can't flow in three-wire systems, the symmetrical components of phase *b* and phase *c* can be derived with phase shift of phase *a* with degrees -120 and 120 respectively as bellow:

$$\begin{bmatrix} u_{bp} \\ u_{bn} \end{bmatrix} = \begin{bmatrix} u_{ap}\measuredangle -\frac{2\pi}{3} \\ u_{an}\measuredangle -\frac{2\pi}{3} \end{bmatrix} \quad \& \quad \begin{bmatrix} u_{cp} \\ u_{cn} \end{bmatrix} = \begin{bmatrix} u_{ap}\measuredangle +\frac{2\pi}{3} \\ u_{an}\measuredangle +\frac{2\pi}{3} \end{bmatrix} \tag{3}$$

Applying counter clockwise rotating d-q transformation matrix to positive sequence and clockwise one to negative sequence and after some manipulation on above equations, the following phasor-type equations are deduced: we have:

$$u_{dp} + ju_{qp} = u_{dqp} = \frac{2}{3}\left[\tilde{u}_{ap} + a\tilde{u}_{bp} + a^2\tilde{u}_{cp}\right] \tag{4}$$

$$u_{dn} + ju_{qn} = u_{dqn} = \frac{2}{3}\left[\tilde{u}_{an} + a^2\tilde{u}_{bn} + a\tilde{u}_{cn}\right] \tag{5}$$

If we perform above routine for DG current, we can obtain the positive and negative sequences of current in d-q frame. The complex output power of the DG inverter is as bellow:

$$\begin{aligned} S_{DG} &= P_{DG} + jQ_{DG} = \frac{3}{2}u_{dq(p,n)}.i^*_{dq(p,n)} \\ &= \frac{3}{2}(e^{jwt}u_{dqp} + e^{-jwt}u_{dqn})(e^{jwt}i_{dqp} + e^{-jwt}i_{dqn})^* \end{aligned} \tag{6}$$

Expanding (6) and setting real and imaginary parts of two sides we obtain following equations:

$$\begin{aligned} P_{DG} &= P_0 + P_{c2}\cos(2\omega t) + P_{s2}\sin(2\omega t) \\ Q_{DG} &= Q_0 + Q_{c2}\cos(2\omega t) + Q_{s2}\sin(2\omega t) \end{aligned} \tag{7}$$

In which:

$$\begin{aligned} P_0 &= \frac{3}{2}(u_{dp}i_{dp} + u_{qp}i_{qp} + u_{dn}i_{dn} + u_{qn}i_{qn}) \\ P_{c2} &= \frac{3}{2}(u_{dn}i_{dn} + u_{qn}i_{qp} + u_{dn}i_{dn} + u_{qp}i_{qn}) \\ P_{s2} &= \frac{3}{2}(u_{dp}i_{qn} - u_{qp}i_{dn} - u_{dn}i_{qp} + u_{qn}i_{dp}) \\ Q_0 &= \frac{3}{2}(u_{qp}i_{dp} + u_{qn}i_{dn} - u_{dp}i_{qp} - v_{dn}i_{qn}) \\ Q_{c2} &= \frac{3}{2}(-u_{dp}i_{qn} + u_{qp}i_{dn} - u_{dn}i_{qp} + u_{qn}i_{dp}) \\ Q_{s2} &= \frac{3}{2}(u_{dp}i_{dn} + u_{qp}i_{qn} - u_{dn}i_{dp} - u_{qn}i_{qp}) \end{aligned} \tag{8}$$

As equations (7) and (8) show, oscillating active and reactive terms appear in DG output power during utility unbalance. By proper control of positive and negative sequence current we can remove the oscillating terms. But in such cases unbalance currents would flow from the inverter and this reduces its operating margin. Thus maximum deliverable power has to be decreased. On the other hand, as we know, some of renewable energies such as PV, FC and wind usually have maximum power point tracking (MPPT) system that conflict with above discussions. Therefore in this paper we prefer to get balanced currents from DG as long as the power oscillation and dc link variation are acceptable. DG reference current will be given by:

$$i^*_{DG} = k.u_p \tag{9}$$

Where u_p is the fundamental positive sequence space vector voltage at point of common coupling (PCC). The power that is delivered by the DG will then be:

$$P_{DG} = u_p.i^*_{DG} = u_p.k.u_p = ku_p^2 \tag{10}$$

Then the constant k will be determined by the condition that DG output power is constant and can be higher or lower than dc component power of the non-linear and/or unbalanced load. Transforming the PCC voltage to stationary α-β reference frame and susbstituting the result in (10), we can write:

$$k = \frac{P_{DG}}{u_{\alpha p}^2 + u_{\beta p}^2} \tag{11}$$

Finally the reference of DG will be given by:

$$\begin{bmatrix} i^*_{\alpha,DG} \\ i^*_{\beta,DG} \end{bmatrix} = \frac{P_{DG}}{u_{\alpha p}^2 + u_{\beta p}^2} \begin{bmatrix} u_{\alpha p} \\ u_{\beta p} \end{bmatrix} \tag{12}$$

The extraction of positive sequence voltage will be described in hybrid filter section. Transforming DG inverter actual currents to α-β reference frame and comparing them with the reference values in (12), error signal is fed to a proportional resonant (PR) controller with the following transfer function:

$$G(s) = K_p + \frac{2K_I\omega_C S}{S^2 + 2\omega_C S + \omega_0^2} \tag{13}$$

Where K_P is the proportional gain, K_I is the resonant gain for the resonant peak adjustment and ω_C is the cutoff frequency for resonant bandwidth control. Control block diagram of DG inverter is shown in Fig. 3.

B. *Hybrid Filter Structure and Its Control Strategy*

Hybrid filter structure is shown in Fig. 4. It consists of three band pass PFs tuned at fundamental frequency of utility and is placed in series with DG and non-linear/unbalanced load and a three-phase three-arm PAF that is connected in parallel with DG, nonlinear load and PFs. The PFs show high impedance at harmonic frequencies that yields in removing of harmonic currents. Although these PFs add small amount of harmonic voltages to load side but the load fundamental voltage is equal to utility one. The aim of active filter is to compensate unbalances of load side current and the reactive power so that balanced sinusoidal currents in phase with positive sequence of fundamental utility voltage are drawn from the utility. Inductors of PFs can be series combination of several mutually coupled smaller inductors. This idea reduces volume and weight of PFs and consequently the hybrid filter. The equivalent inductance of PFs with this topology is equal to:

$$L_{BF} = L_{BF1} + L_{BF2} + L_{BF3} + 2(M_{12} + M_{23} + M_{13}) \tag{14}$$

As the PF's impedance is limited at harmonic frequency thus always some low order harmonics can flow through it, especially under high load current condition, which is compensated by AF. The control method and the block diagram of active part were described in [14]. Thus only reference signal for AF and positive sequence extraction of utility voltage that is usable in DG inverter control and AF, is described here again. AF reference current is as bellow:

$$\begin{aligned} i^*_{fd} &= -U_{dp}\frac{U_{dp}I_{BFd,\,fund} + U_{qp}I_{BFq,\,fund}}{U_{dp}^2 + U_{qp}^2} - i_{BFd} \\ i^*_{fq} &= -U_{qp}\frac{U_{dp}I_{BFq,\,fund} + U_{qp}I_{BFq,\,fund}}{U_{dp}^2 + U_{qp}^2} - i_{BFq} \end{aligned} \tag{15}$$

Using the symmetric component method, asymmetric and distorted grid voltages, U_a, U_b and U_c are decomposed into positive, negative and zero sequence components. It can be expressed as [14]:

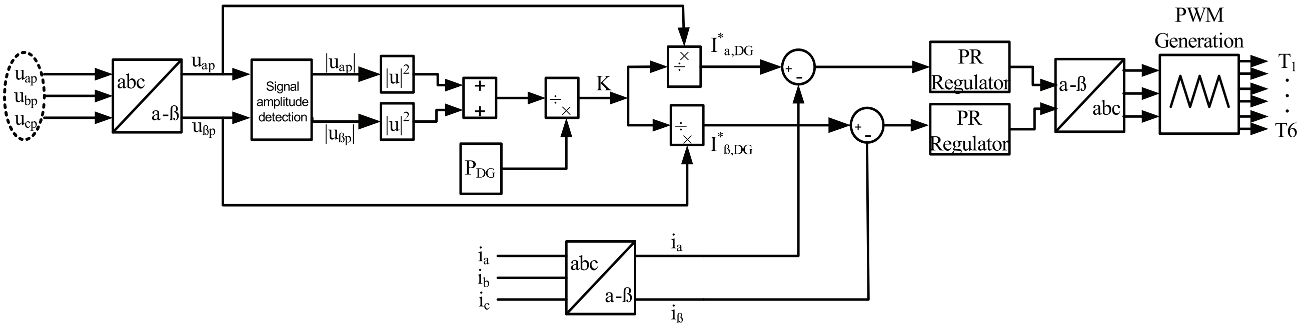

Fig. 3. Control block diagram of DG inverter

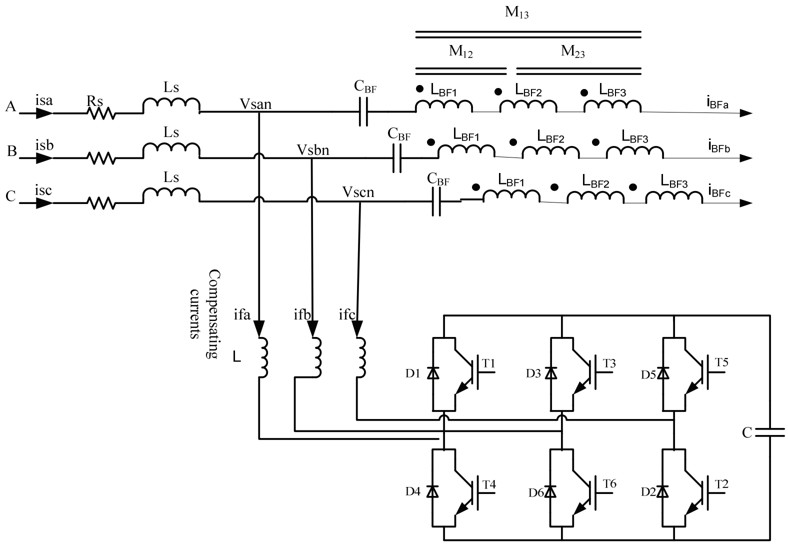

Fig. 4. Hybrid filter structure

$$
\begin{aligned}
U_a &= \sum_{n=1}^{\infty} [b_{(n^+)} \sin(n\omega t + \phi_{(n^+)}) \\
&\quad + b_{(n-)} \sin(n\omega t + \phi_{(n^-)}) + b_{(0)} \sin(n\omega t + \phi_{(0)}) \\
U_b &= \sum_{n=1}^{\infty} [b_{(n^+)} \sin(n\omega t + \phi_{(n^+)} - \frac{2\pi}{3}) \\
&\quad + b_{(n-)} \sin(n\omega t + \phi_{(n^-)} + \frac{2\pi}{3}) + b_{(0)} \sin(n\omega t + \phi_{(0)}) \\
U_c &= \sum_{n=1}^{\infty} [b_{(n^+)} \sin(n\omega t + \phi_{(n^+)} + \frac{2\pi}{3}) \\
&\quad + b_{(n-)} \sin(n\omega t + \phi_{(n^-)} - \frac{2\pi}{3}) + b_{(0)} \sin(n\omega t + \phi_{(0)})
\end{aligned}
\tag{16}
$$

where $b_{(n+)}$, $b_{(n-)}$ and $b_{(0)}$ are positive, negative and the zero sequence component magnitudes respectively, for each harmonic order. Transforming (16) to d-q-0 coordinates, we have:

$$
\begin{aligned}
U_d &= b_{(n^+)} \cos(\phi_{(n^+)}) + \sum_{n=2}^{\infty} b_{(n^+)} \cos[(n-1)\omega t + \phi_{(n^+)}] \\
&\quad - \sum_{n=2}^{\infty} b_{(n^-)} \cos[(n-1)\omega t + \phi_{(n^+)}] \\
U_q &= b_{(n^+)} \sin(\phi_{(n^+)}) + \sum_{n=2}^{\infty} b_{(n^+)} \sin[(n-1)\omega t + \phi_{(n^+)}] \\
&\quad - \sum_{n=2}^{\infty} b_{(n^-)} \sin[(n-1)\omega t + \phi_{(n^+)}] \\
U_0 &= \sum_{n=1}^{\infty} b_{(n^0)} \sin[(n-1)\omega t + \phi_{(n^0)}]
\end{aligned}
\tag{17}
$$

Using two low pass filters we can extract dc components as bellow:

$$
\begin{bmatrix} U_{dp} \\ U_{qp} \end{bmatrix} = \begin{bmatrix} b_{(n^+)} \cos(\phi_{(n^+)}) \\ b_{(n^+)} \sin(\phi_{(n^+)}) \end{bmatrix}
\tag{18}
$$

For using these positive sequences in DG inverter control, it is necessary to transform them to *abc* coordinates.

4. Simulation results

In order to verify the proposed hybrid compensation system, it is simulated under non-ideal utility voltage using PSB of Matlab software. A typical unbalance three-phase diode rectifier RC load is used for simulations. Fig. 5 shows the simulation results under unbalanced/distorted utility voltage. As this figure shows, load current harmonics are removed by PF and balanced and sinusoidal current inphase with PCC positive sequence fundamental voltage is injected to the load. Finally PAF compensates for unbalanced currents. In this way balanced and sinusoidal current inphase with fundamental positive sequence of utility voltage is delivered to the load from the utility. DC-link voltage of AF is regulated at desired values and the other one for DG inverter is provided properly with SOFC.

5. Conclusion

This paper has proposed a new hybrid compensation system and new control methods for power quality improvement in an electrical utility with DG units. DG inverter was controlled in such a way that it delivered balanced and sinusoidal currents in phase with fundamental positive sequence of PCC voltage and the SOFC was responsible for active power generation. The hybrid filter was composed of series PFs and a PAF. Mutually coupled inductances were used in PFs configuration and this would reduce volume, weight and overall cost of the system. The PFs were tuned at fundamental frequency of utility and this led to remove harmonic currents and significant decrease in PAF rating. PAF was controlled to compensate unbalanced current, reactive power and small harmonic currents that were remained due to PFs limitation. Finally as we saw, balanced and sinusoidal currents in-phase with fundamental positive sequence of source voltage was drawn from utility. The computer simulations using PSB of Matlab software showed the effectiveness of proposed hybrid structure and new control methods applied to PAF and DG inverter.

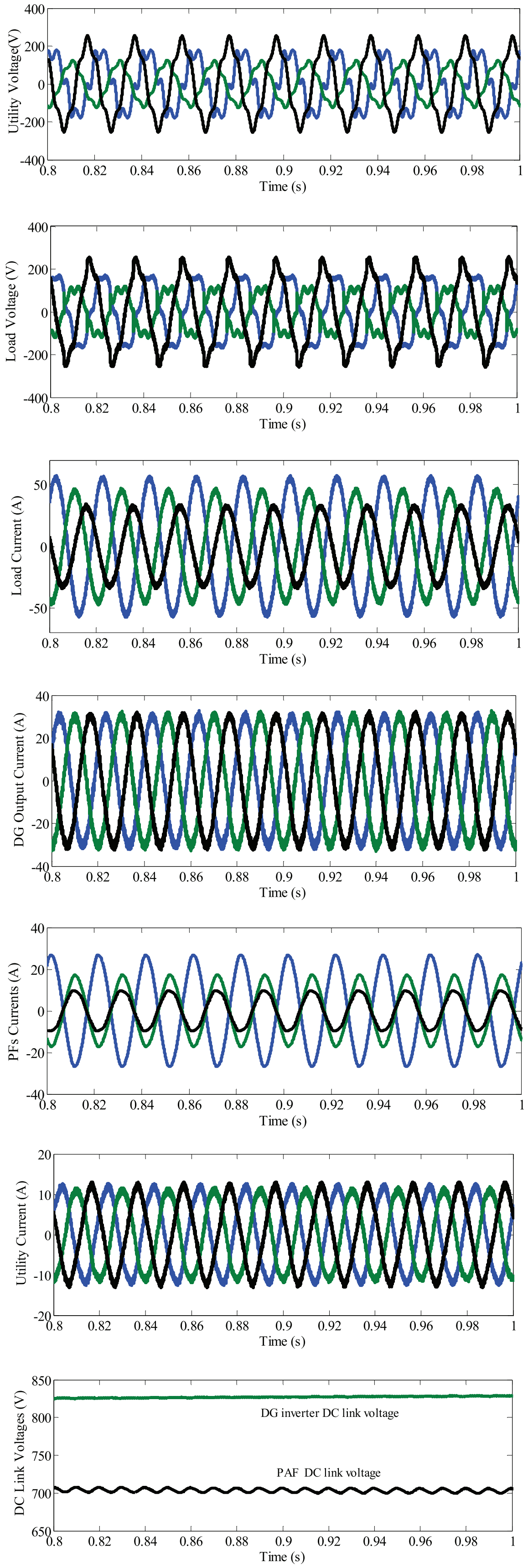

Fig. 5. Simulation results under non-ideal source voltage

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