A New Flexible Distributed Generation Unit for Active Power Generation and Harmonic Compensation Under Non-Ideal Source Voltages Condition

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Abstract

In this paper a flexible distributed generation (FDG) with a new control scheme is proposed for the purpose of contributing to power generation and harmonic compensation under non-ideal source voltages. The proposed FDG consists of a Solid Oxide Fuel Cell unit (SOFC) as power source and a three-arm full bridge DC-AC PWM inverter as utility interface. The new control scheme enables the FDG to deliver sinusoidal active currents in-phase with positive sequence of source fundamental voltages and also to compensate harmonic currents which are drawn by non-linear load under non-ideal source voltage. The proportional resonant (PR) controllers are used for reference signal tracking. In order to investigate the proposed FDG, simulations will be conducted using PSB of Matlab Simulink software. The results show the validity of the proposed FDG.

1. Introduction

Distributed Generation (DG) has been gaining attention in recent times. In conventional power systems, power is generated in central generator stations and transmitted downstream through transmission and distribution networks. However, with the introduction of DGs, this unidirectional power flow concept has been changed and circuits have been modified to make room for the DGs. DGs are of many types. Among them are wind, bio-gas, fuel cells and solar cells. These sources are connected to grid through inverters, and their main function is to deliver active power into the grid [1]. The integration of the DG with the utility distribution network offers a number of technical, environmental and economic benefits. It also gives a great opportunity for distribution utilities to improve the performance on networks by reducing its losses [2].

On the other hand the increasing use of non-linear loads such as switch mode power converters, power electronic operated adjustable speed drives, fluorescent lamps, etc in domestic and industrial applications, injects high amount of harmonic currents in to the electrical grid and this degrade power quality. This harmonics increase the losses in all components connected to the grid, and cause voltage distortion problems. Custom power devices such as LC tuned passive filters, active power filters and hybrid filters as combination of two previous ones have been successfully implemented for harmonic compensation and power quality improvement [3].

It is cost-effective to implement DGs to mitigate power quality problems beside active power generation. The DGs can be controlled to inject load reactive power at point of common coupling (PCC) and this will modify voltage profile of electrical utility. Also they can be implemented as harmonic filters for compensation of harmonic currents produced by non-linear loads. Such multi function DGs are called Flexible DG (FDG) [1]-[2], [4]-[6].

Power quality improvement and active power generation becomes more serious under non-ideal source voltages conditions. The non-ideality of source voltage has limiting effects on the operation region of DG inverter. Thus in order to achieve satisfying performance of FDG under such conditions, it is important to apply proper reference signal generation technique. The technical challenges associated with the FDG can be subdivided into three categories:

- The system interface to the grid.
- Operation and control of the DG.
- Planning and design.

In this work we focus on the two first categories. This paper deals with a new FDG under non-ideal source voltages conditions. The FDG consists of a SOFC as power source and a three-arm full bridge DC-AC inverter as utility interface. A new control scheme is applied to FDG that enables it to deliver sinusoidal current in-phase with positive sequence of source fundamental voltage. Also the proposed FDG can compensate for load harmonic currents under non-ideal source voltage so that balanced and sinusoidal currents are drawn from the electrical grid. In order to FDG output currents track their reference value, PR controllers are implemented. The performance of the proposed FDG is verified using power simulink blockset (PSB) of Matlab Simulink software.

2. Proposed FDG schematic and its control method

The test system single line configuration and proposed FDG schematic are shown in Fig. 1 and Fig. 2 respectively. The FDG is connected in parallel with non-linear load and electrical utility at PCC. It consists of a SOFC as power source, a DC-DC boost converter and a three-phase PWM inverter. As we know, the output voltage of FC is very low thus it is necessary to amplify its output voltage to higher values. This is done by boost converters. After boosting the FC output voltage, the voltage is fed to the PWM inverter to produce both sinusoidal active current and required harmonic current demanded by non-linear load. Dynamic equations and control block diagram of SOFC are investigated in [7]. Here only the dynamic equations are described. The electromechanical reactions occurring in SOFC utilizing H_2 and O_2 are:

$$H_2 + O^{=} \rightarrow H_2O + 2e^- \quad (anode) \tag{1}$$

$$\frac{1}{2}O_2 + 2e \rightarrow O^{=} \quad (cathode) \tag{2}$$

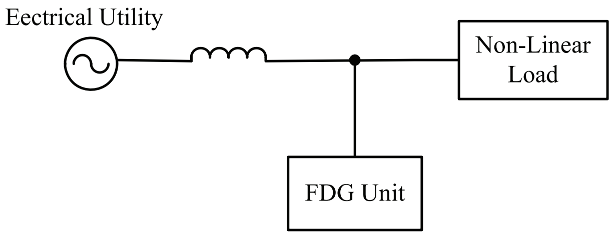

Fig. 1. Test system configuration

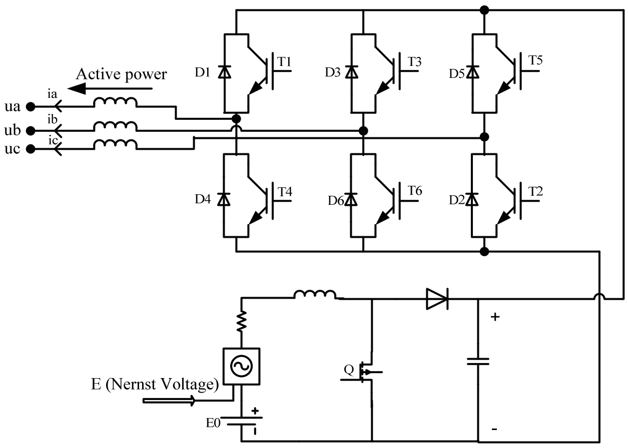

Fig. 2. Proposed FDG configuration

The overall SOFC reaction is

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{3}$$

The performance of SOFC is defined by its Nernst potential represented as cell voltage. This equation provides a relationship between the ideal standard potential (E_0) for the cell reaction, the ideal equilibrium potential (E) at the other temperatures and partial pressures of reactants and products. The corresponding Nernst equation is:

$$E = E_0 + \frac{RT}{2F}\ln\left(\frac{P_{H2}[P_{o2}]^{1/2}}{P_{H2O}}\right) \tag{4}$$

Fuel utilization factor is the ratio between the fuel flow that react and the input fuel flow. Here we have:

$$U_f = \frac{q_{H2}^{r}}{q_{H2}^{in}} \quad \& \quad 0.8 \le U_f \le 0.9 \tag{5}$$

The hydrogen flow reactant and the output current can be related by:

$$q_{H2}^{r} = \frac{N_0 I_{fc}^{r}}{2F} = 2K_r I_{fc}^{r} \tag{6}$$

Combining equations (5) and (6) SOFC current is limited as bellow:

$$\frac{0.8q_{H2}^{in}}{2K_r} \le I_{fc}^{r} \le \frac{0.9q_{H2}^{in}}{2K_r} \tag{7}$$

Concerning the control of FDG inverter under unbalanced voltage it is advantageous to investigate its output power. Under such condition three-phase FDG inverter output voltage can be written using symmetrical components method. Thus we have:

$$\begin{aligned} u_a &= u_{ap} + u_{an} + u_{az} \\ u_b &= u_{bp} + u_{bn} + u_{bz} \\ u_c &= u_{cp} + u_{cn} + u_{cz} \end{aligned} \tag{8}$$

In which:

$$\begin{bmatrix} u_{ap} \\ u_{an} \\ u_{az} \end{bmatrix} = \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad \& \quad a = e^{j\frac{2\pi}{3}} \tag{9}$$

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:

$$\begin{bmatrix} u_{bp} \\ u_{bn} \end{bmatrix} = \begin{bmatrix} u_{ap}\measuredangle -\frac{2\pi}{3} \\ u_{an}\measuredangle -\frac{2\pi}{3} \end{bmatrix} \quad \& \quad \begin{bmatrix} u_{cp} \\ u_{cn} \end{bmatrix} = \begin{bmatrix} u_{ap}\measuredangle +\frac{2\pi}{3} \\ u_{an}\measuredangle +\frac{2\pi}{3} \end{bmatrix} \tag{10}$$

Applying counter clockwise rotating d-q transformation matrix to positive sequence and clockwise one to negative sequence, we have:

$$\begin{aligned} \begin{bmatrix} u_{dp} \\ u_{qp} \end{bmatrix} &= \frac{2}{3} \begin{bmatrix} \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} u_{ap} \\ u_{ap} \\ u_{ap} \end{bmatrix} \\ &= (T_{abc}^{dq})_{clockwise} \begin{bmatrix} u_{ap} \\ u_{ap} \\ u_{ap} \end{bmatrix} \\ \begin{bmatrix} u_{dn} \\ u_{qn} \end{bmatrix} &= \frac{2}{3} \begin{bmatrix} -\sin(\omega t) & -\sin(\omega t + \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t + \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} u_{an} \\ u_{an} \\ u_{an} \end{bmatrix} \\ &= (T_{abc}^{dq})_{counterclockwise} \begin{bmatrix} u_{ap} \\ u_{ap} \\ u_{ap} \end{bmatrix} \end{aligned} \tag{11}$$

After some manipulation on above equations, the following phasor type equations are deduced:

$$u_{dp} + ju_{qp} = u_{dqp} = \frac{2}{3}\left[\tilde{u}_{ap} + a\tilde{u}_{bp} + a^2\tilde{u}_{cp}\right] \tag{12}$$

$$u_{dn} + ju_{qn} = u_{dqn} = \frac{2}{3}\left[\tilde{u}_{an} + a^2\tilde{u}_{bn} + a\tilde{u}_{cn}\right] \tag{13}$$

If we perform above routine for DG current, we can obtain the positive and negative sequences of current in d-q frame.

Then the complex output power of the DG inverter is as bellow:

$$\begin{aligned} S_{DG} &= P_{DG} + jQ_{DG} = \frac{3}{2}u_{dq(p,n)}.i^*_{dq(p,n)} \\ &= \frac{3}{2}(e^{jwt}u_{dqp} + e^{-jwt}u_{dqn})(e^{jwt}i_{dqp} + e^{-jwt}i_{dqn})^* \end{aligned} \tag{14}$$

Expanding (14) and setting real and imaginary parts of two sides we obtain following equations:

$$\begin{aligned} P_{DG} &= P_0 + P_{c2}\cos(2\omega t) + P_{s2}\sin(2\omega t) \\ Q_{DG} &= Q_0 + Q_{c2}\cos(2\omega t) + Q_{s2}\sin(2\omega t) \end{aligned} \tag{15}$$

In which:

$$\begin{aligned} P_0 &= \frac{3}{2}(u_{dp}i_{dp} + u_{qp}i_{qp} + u_{dn}i_{dn} + u_{qn}i_{qn}) \\ P_{c2} &= \frac{3}{2}(u_{dn}i_{dn} + u_{qn}i_{qp} + u_{dn}i_{dn} + u_{qp}i_{qn}) \\ P_{s2} &= \frac{3}{2}(u_{dp}i_{qn} - u_{qp}i_{dn} - u_{dn}i_{qp} + u_{qn}i_{dp}) \\ Q_0 &= \frac{3}{2}(u_{qp}i_{dp} + u_{qn}i_{dn} - u_{dp}i_{qp} - v_{dn}i_{qn}) \\ Q_{c2} &= \frac{3}{2}(-u_{dp}i_{qn} + u_{qp}i_{dn} - u_{dn}i_{qp} + u_{qn}i_{dp}) \\ Q_{s2} &= \frac{3}{2}(u_{dp}i_{dn} + u_{qp}i_{qn} - u_{dn}i_{dp} - u_{qn}i_{qp}) \end{aligned} \tag{16}$$

As seen from equations (15) and (16) oscillating active and reactive terms appear in DG output power during utility unbalances. By proper control of positive and negative sequence currents 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 conflicts 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:

$$i^*{}_{DG} = k.u_p \tag{17}$$

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

$$P_{DG} = u_p.i^*{}_{DG} = u_p.k.u_p = ku_p^2 \tag{18}$$

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

$$k = \frac{P_{DG}}{u_{\alpha p}^2 + u_{\beta p}^2} \tag{19}$$

Finally the reference of DG will be given by:

$$\begin{bmatrix} i^*_{\alpha,DG} \\ i^*_{\beta,DG} \end{bmatrix} = \frac{P_{DG}}{u_{\alpha p}^2 + u_{\beta p}^2}\begin{bmatrix} u_{\alpha p} \\ u_{\beta p} \end{bmatrix} \tag{20}$$

The extraction of positive sequence voltage will be described in the next section. Transforming DG inverter actual currents to α-β reference frame and comparing them with the reference values in (20), error signal is fed to a proportional resonant (PR) controller with the following transfer function:

$$G(s) = K_p + \frac{2K_I\omega_C S}{S^2 + 2\omega_C S + \omega_0^2} \tag{21}$$

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. The controller in (21) is actually a practical form of ideal PR controller that can be mathematically derived by transforming a synchronous frame controller to stationary frame.

In order to compensate non-linear load harmonic currents through FDG, it is necessary to measure load current and to extract its harmonic and/or its unbalance currents (unbalance current can present due to unbalance source voltage) and add these currents to FDG reference signals. In order to extract fundamental positive sequence of non-ideal source voltage a new method was proposed in [8]. It can be applicable for both current and voltage in this paper.

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

$$\begin{aligned} U_a &= \sum_{n=1}^{\infty}[\,b_{(n^+)}\sin(n\omega t + \phi_{(n^+)}) \\ &\quad + b_{(n-)}\sin(n\omega t + \phi_{(n^-)}) + b_{(0)}\sin(n\omega t + \phi_{(0)}) \\ U_b &= \sum_{n=1}^{\infty}[\,b_{(n^+)}\sin(n\omega t + \phi_{(n^+)} - \frac{2\pi}{3}) \\ &\quad + b_{(n-)}\sin(n\omega t + \phi_{(n^-)} + \frac{2\pi}{3}) + b_{(0)}\sin(n\omega t + \phi_{(0)}) \\ U_c &= \sum_{n=1}^{\infty}[\,b_{(n^+)}\sin(n\omega t + \phi_{(n^+)} + \frac{2\pi}{3}) \\ &\quad + b_{(n-)}\sin(n\omega t + \phi_{(n^-)} - \frac{2\pi}{3}) + b_{(0)}\sin(n\omega t + \phi_{(0)}) \end{aligned} \tag{22}$$

where ($b_{(n+)}$, $b_{(n-)}$, $b_{(0)}$) and ($\phi_{(n^+)}$, $\phi_{(n^-)}$, $\phi_{(0)}$) are the positive, negative and the zero sequence component magnitudes and phases respectively for each harmonic order.

Transforming (22) to d-q-0 coordinates using $T^{dq0}{}_{abc(clock\ wise)}$, we have:

$$
\begin{aligned}
U_d &= b_{(n^+)}\cos(\phi_{(n^+)}) + \sum_{n=2}^{\infty} b_{(n^+)}\cos[(n-1)\,\omega t + \phi_{(n^+)}] \\
&\quad - \sum_{n=2}^{\infty} b_{(n^-)}\cos[(n-1)\,\omega t + \phi_{(n^+)}] \\
U_q &= b_{(n^+)}\sin(\phi_{(n^+)}) + \sum_{n=2}^{\infty} b_{(n^+)}\sin[(n-1)\,\omega t + \phi_{(n^+)}] \\
&\quad - \sum_{n=2}^{\infty} b_{(n^-)}\sin[(n-1)\,\omega t + \phi_{(n^+)}] \\
U_0 &= \sum_{n=1}^{\infty} b_{(n^0)}\sin[(n-1)\,\omega t + \phi_{(n^0)}]
\end{aligned} \tag{23}
$$

Using two low pass filters we can extract dc components:

$$
\begin{bmatrix} U_{dp} \\ U_{qp} \end{bmatrix} = \begin{bmatrix} b_{(n^+)}\cos(\phi_{(n^+)}) \\ b_{(n^+)}\sin(\phi_{(n^+)}) \end{bmatrix} \tag{24}
$$

For using these positive sequences in DG inverter control, it is necessary to transform them to *abc* and then to $\alpha\beta$ coordinates. Applying (24) in FDG inverter control, enables it to operate properly under non-ideal source voltage.

Concerning load harmonic and/or unbalanced currents extraction, at first we should extract fundamental positive sequence of the load currents with the same routine as done for the voltages, then after transforming the obtained signals to abc frame, the result should be subtracted from the measured ones obtained from load phases. The proposed FDG control block diagram is shown in Fig. 3.

3. Simulation results

In order to verify the validity of the proposed control scheme and satisfying operation of FDG, the whole system was simulated in PSB of Matlab Simulik software. A typical R-L diode rectifier load was used for simulation. The source voltage is changed from ideal one to unbalance and unbalanced/harmonic polluted ones

The first simulation was carried out with out any load to show the proposed FDG capability in injecting sinusoidal active currents in-phase with positive sequence of source fundamental voltages at any source voltage conditions. As shown in Fig. 4, the proposed goal has been acheived successfully during all conditions of source voltage. Also during voltage unbalance the injected active power through FDG contains oscilating terms as prooved in (16). FDG DC link voltage is regulated effectively and its variation during voltage changes is negligible.

The second simulation that is shown in Fig. 5 was conducted by applying the proposed non-linear load to show the proposed FDG capability in injecting load harmonic current and active power generation simultaneously. As shown from Fig. 5 sever harmonic currents are drwan from utility. İn such a condition the FDG injects load harmonic currents besides of generationg active power. Thus balanced and sinusoidal currents in-phase with positive sequence of source fundamental voltage under any source voltage conditions, are drwan from utility.

4. Conclusion

This paper has proposed a new FDG with new control scheme. İt was consisted of SOFC as power source and a three-arm PWM inverter as utility interface. The new control scheme enabled the FDG to generate sinusoidal active current inphase with positive sequence of source fundamental voltage and also using the new control scheme FDG was able to compensate load harmonic currents. Finally balanced and sinusoidal current in-phase with positive sequence of source fundamental voltage was drawn from electrical utility. Simulatins that has been carried out in power simulink blockset (PSB) of MATLAB showed the validity of the proposed FDG and its control scheme.

5. References

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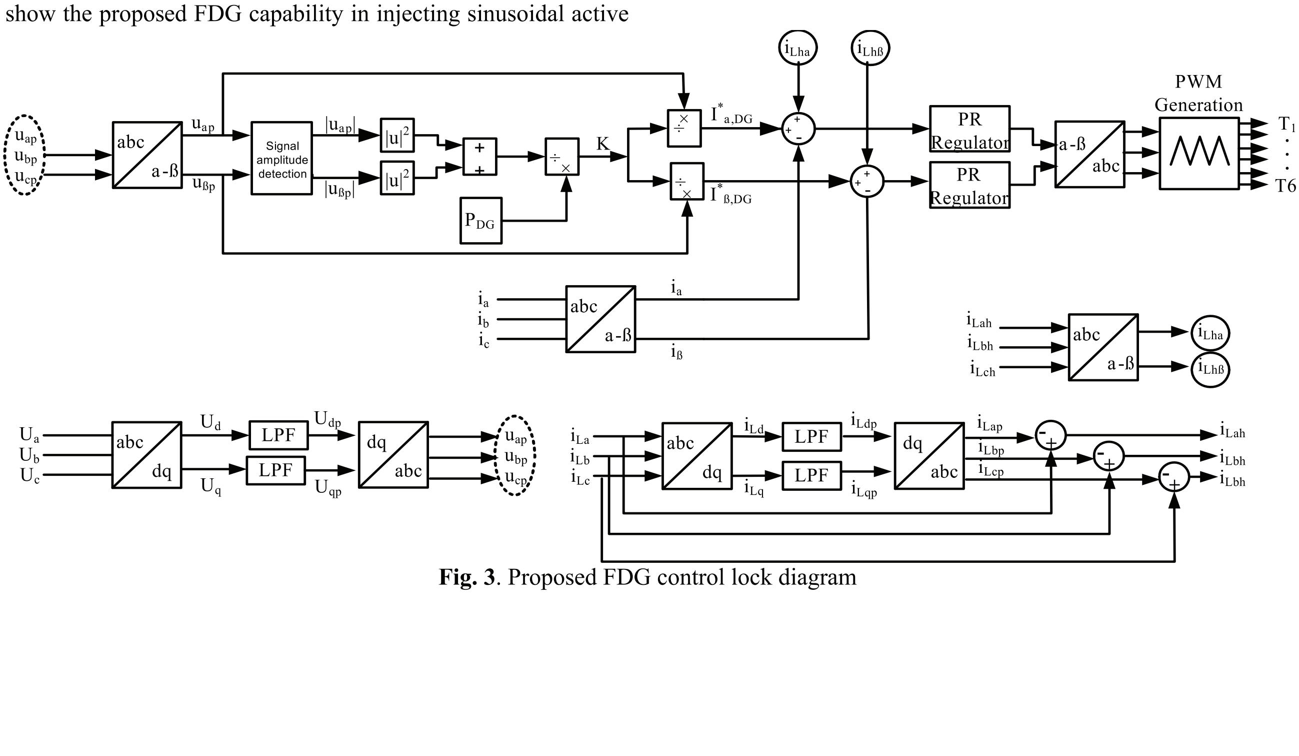

Fig. 3. Proposed FDG control lock diagram

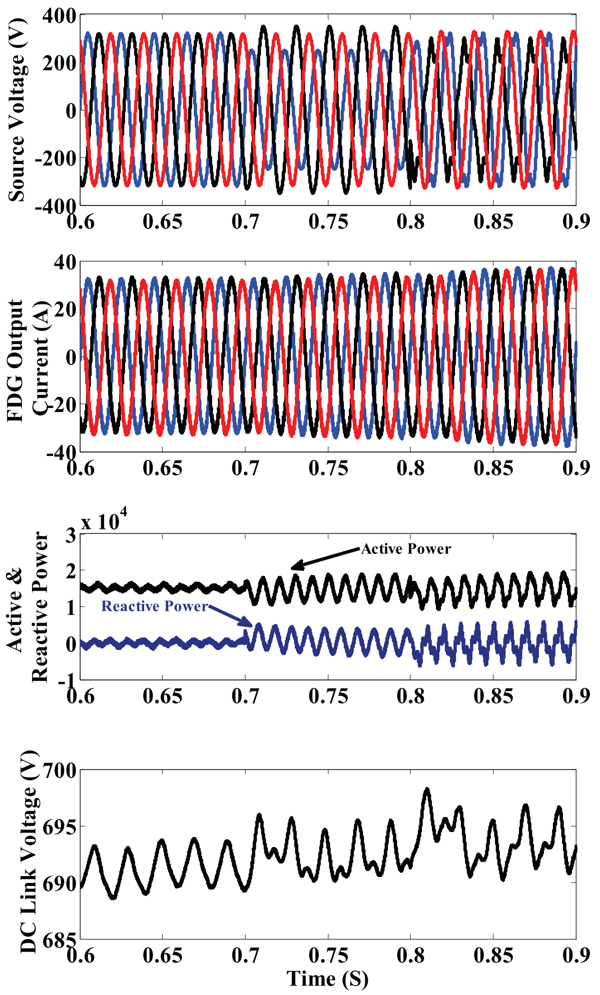

Fig. 4. Simulation results without non-linear load

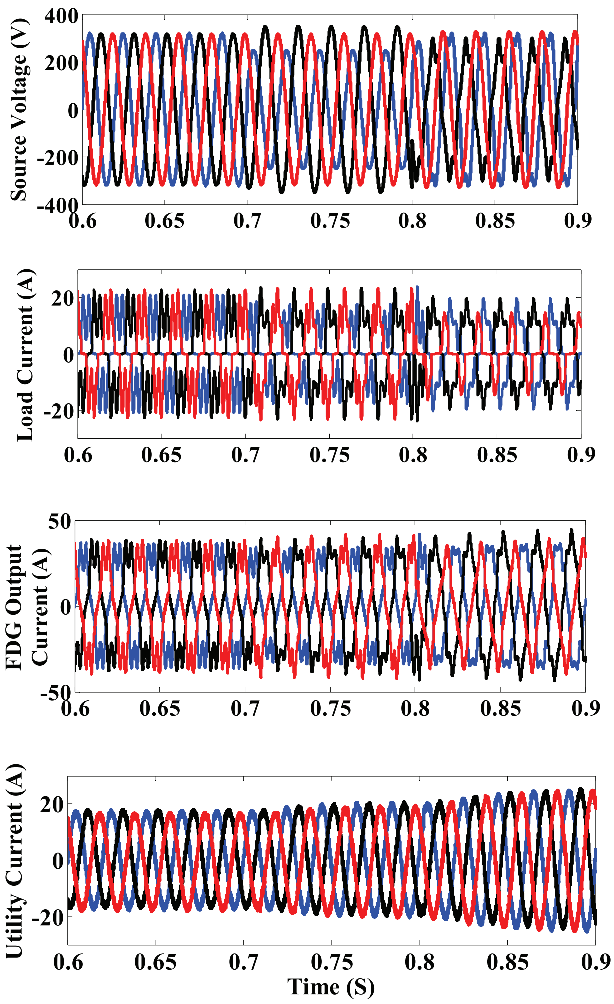

Fig. 5. Simulation results with non-linear load

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