Power Factor Improvement of DC/DC Converters for Micro-turbines

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Abstract. The distributed generation interconnection to the power system can have impact not only on the power flow, but also on power quality of customers, and utilities. This paper proposes a multi-function nonlinear link for distribution generation systems. The main function of this link is to regulate the active power supplied from distribution generation to the utility. The link can also supply reactive power to the utility to enable unity power factor operation or to regulate the voltage at the point of common coupling. This link can also be controlled to mitigate power quality problems. Genetic algorithm is also used for the optimization of parameters of the power factor correction controller. The simulation performed in MATLAB/Simulink validates the effectiveness of the proposed power factor scheme.

Key words

Micro-Turbine, DC/DC Converter, Power Quality, Genetic Algorithm, Distribution Generation

1. Nomenclature

L_d , L_q	d and q axes inductances
R	Resistance of the stator windings
i_d , i_q	d and q axes currents
v_d , v_q	d and q axes voltages
ω_r	Angular velocity of the PMSM rotor
λ	Flux-linkages induced by the permanent magnets in the stator windings.
P	Number of pole-pairs
Te	Electromagnetic torque
j	Combined inertia of rotor and load
F	Combined viscous friction of rotor and load
θ	Rotor angular position
T_m	Shaft mechanical torque
V_{in}	input voltage of DC/DC converter
T_s	switching cycle
i_L	inductor current in the DC/DC converter
V_o	output voltage of DC/DC converter
d	duty cycle in each switching cycle
i_{ref}	reference value of i_L
V_{ref}	reference value of V_o
k_{PID}	is the peak value of the reference current
K_P	proportional gain of PI controller
K_i	integral gain of PI controller

2. Introduction

The fundamental concepts for the penetration of Distribution Generation (DG) technologies are the high efficiency, flexibility and reliability of the energy conversion process and the limited emission of pollutants as compared to conventional power plants. Moreover, they provide load management and a number of significant local benefits .The integration of the increasing part of DG within the existing infrastructure requires a full understanding of its impact on the distribution feeders and its interaction with the loads. DG sources could have positive impact on the operation of power systems to which they are connected. Voltage control, stability, and system protection have been studied in the literature as the operational aspects which require full understanding [1-4].

In recent years, power quality has become a significant issue for both power suppliers and customers [5-6]. The DG interconnection to the power system can have impact not only on the power flow and power quality, but also on customers, and utilities. The impacts may be considerable depending on the distribution system and DG characteristics. The DG can improve the power quality, the system reliability and reduce the losses. Their connection to the distribution system can also result in operational difficulties. Thus, DGs should meet various operating requirements of utilities or power system operators. However, the well-designed and well-controlled DGs can improve power quality. A new control system for independent operation of parallel connected DG Units in distribution DC Systems has been proposed in [6]. Many aspects of interconnection of DG units to the grid have been presented in [7-9]. Also, neural implementation of micro-grid central controllers has been discussed in [10]. These DGs can protect the local loads against the voltage sag and swell, and also compensate harmonics. The power quality aspects of interconnection of DG to the grid have been considered in [11-13]. In [11], a control scheme for the DG interface to mitigate power quality problems has been presented. Besides, an inverter based flexible DG (FDG) with its control scheme has been introduced in [12] to improve power quality in a weak power system. Also, current harmonics analysis of the DG interconnection to the grid is discussed in [13].

The micro-turbine generator (MTG) has emerged as a viable source of electric energy in DG systems. It can also provide power demand for remote military/commercial applications, and as a stand-alone generator unit. An MTG unit is usually a high-speed (up to 120,000 rpm) machine with an output power of a few hundred kilowatts, and output frequency of 400 Hz (400 Hz to several kHz). Thus, it should be interfaced through a power electronic converter to a load/utility system. The converter provides conversion control of frequency as well as control of the output voltage and power flow of the MTG-converter module [14-15]. Two methods have been presented to convert the high frequency voltage of MTG to the desired 50 or 60 Hz voltage; one, using the rectifier-inverter pair [15-17], and two, using matrix converter [18].

This paper proposes a multi-function nonlinear link for DG systems. The main function of this link is to regulate the active power supplied from a DG to the utility. It should be noted that the link can also supply reactive power to the utility to enable unity power factor operation or to regulate the voltage at the point of common coupling (PCC). This link can also be controlled to compensate the harmonics generated from nonlinear loads to mitigate power quality problems. A DC/DC converter is implemented to eliminate harmonics on the AC side and correct the power factor. A distribution generation with this multi-function interface is known as flexible distribution generation (FDG). It alleviates most of the distribution system problems without using any custom power devices. The simulation performed in MATLAB/Simulink validates the effectiveness of the proposed power factor scheme in harmonic elimination and power factor improvement.

3. System Under Study

Figure 1 demonstrates the configuration of the system under study. Here, the DC input voltage to the shunt converter comes from a rectified DG through a smoothing capacitor *C*, the transformer (*T*), and the current smoothing filter. The converter manages the amount of current I_c injected to the utility. The main goal of this paper is to eliminate the harmonic contents of the input current of diode rectifier and to improve the power factor from the standpoint of the output current of MTG. In the next section, power factor correction scheme is introduced to eliminate the harmonics and improve the power factor.

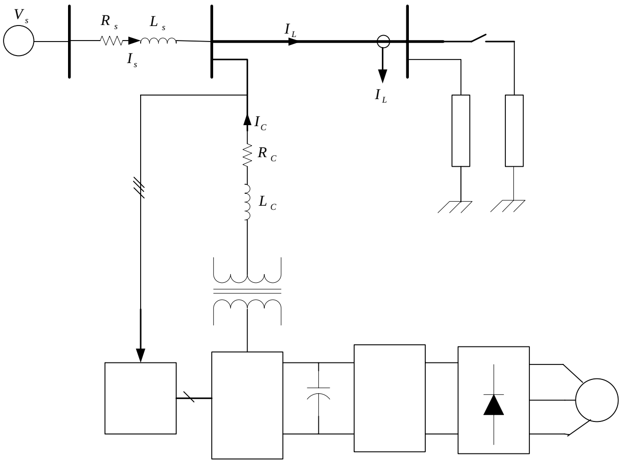

Fig. 1 Configuration of the system under study

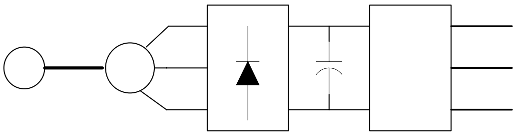

Fig. 2 The configuration of a MTG system

4. Proposed Power Factor Correction Scheme for Micro Turbine Generator

A. MTG System

Fig. 2 depicts the basic components of a micro-turbine generation system. A simplified single-shaft gas turbine with control systems which is implemented in MATLAB/Simulink environment is shown in Fig. 3. The model consists of temperature control, fuel control, turbine dynamics, speed governor and acceleration control blocks which has previously been developed in MATLAB/Simulink environment [19-20]. In this paper, a lead-lag transfer function is used to represent the speed controller. The governor controls with parameters gain, X, Y and Z can be adjusted so that to act with a droop or as an isochronous governor. During turbine startup, acceleration control is used primarily to limit the rate of the rotor acceleration prior to reaching the operating speed. At rated speed, the acceleration control can be eliminated in the modeling. The output of the governor goes to a low value select to produce a value for the fuel demand signal (V_{ce}). The other signal into the low-value select is from the temperature controller. The per-unit value of mechanical power on the basis of turbine power at steady state, corresponds directly to the per-unit value for V_{ce}. The fuel-flow controls as a function of V_{ce}, are shown in a series of blocks including the valve position and flow dynamics. The value of V_{ce}, is scaled by the gain value of 0.77 and offset by the value of fuel-flow at no load with rated speed condition [19-20]. The time delay preceding the fuel-flow controls represents the delays in the governor control. The fuel flow, burned in the combustor produces the turbine torque and the exhaust gas temperature measured by a thermocouple. Normally the reference temperature value is higher than

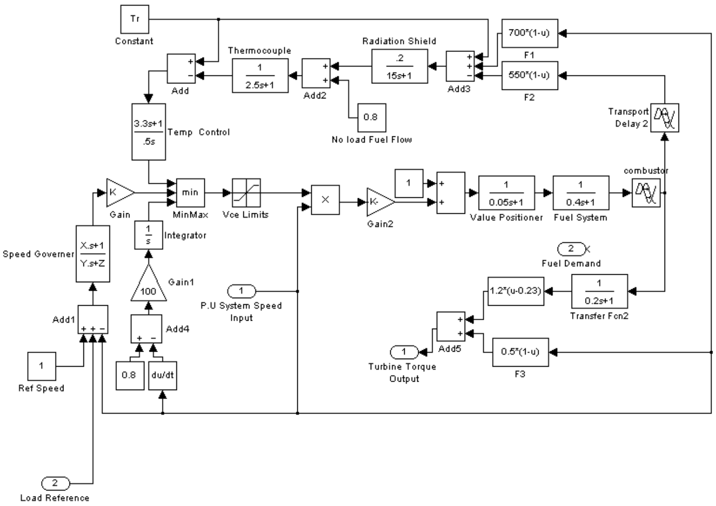

Fig.3 Detailed model of a micro-turbine implemented in Simulink

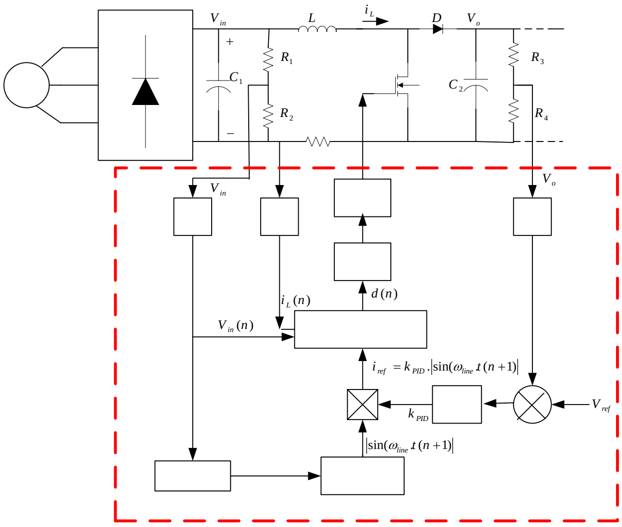

Fig. 4 Digital implementation of PFC system

the thermocouple output and this forces the output from the temperature control to stay on the maximum limit permitting uninhibited governor/speed control. When the thermocouple output exceeds the reference temperature, the temperature error becomes negative and it starts lowering the temperature control output. If the temperature control output becomes lower than the governor output, the former value will pass through the low-value select to limit the output, and the unit will operate on temperature control.

B. High-Speed Permanent Magnet Synchronous Machine

The model adopted for the generator is a two-pole permanent magnet synchronous machine (PMSM) with a non-salient rotor [21]. The electrical and mechanical parts of the machine are each represented by a second-order state-space model. The flux induced by the permanent magnets in the stator is assumed to be sinusoidal, which implies that electromotive forces are sinusoidal. The following equations expressed in the rotor reference frame (dq frame) are used for a PMSM.

$$\frac{di_d}{dt} = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d - \frac{L_q}{L_d}p\omega_r i_q \tag{1}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q - \frac{L_d}{L_q}p\omega_r i_d - \frac{\lambda p\omega_r}{L_q} \tag{2}$$

$$T_e = 1.5p(\lambda i_q + (L_d - L_q)i_d i_q) \tag{3}$$

$$\frac{d\theta}{dt} = \omega_r \tag{4}$$

C. Proposed Power Factor Correction Scheme

The boost DC/DC converter topology used in power factor correction (PFC) implementation is shown Fig. 4. The proposed digital control PFC algorithm is derived based on the continuous conduction mode (CCM) of operation of a boost converter. Switching frequency is much higher than the line frequency. So, the input voltage, V_{in}, can be assumed as a constant in one switching cycle, T_s [22]. Equations (5) and (6) describe the inductor current in one switching cycle when the switch is on or off, respectively [23].

$$\frac{di_L}{dt} = V_{in} \quad t_n \le t < t_n + d_n T_s \tag{5}$$

$$L\frac{di_L}{dt} = V_{in} - V_o \quad t_n + d_n T_s \le t < t_{n+1} \tag{6}$$

In the discrete form, as $\Delta t \to 0$, then $\frac{di_L}{dt} = \frac{i_L(n+\Delta t) - i_L(n)}{\Delta t}$, and hence:

$$i_L(n+1) = i_L(n) + \frac{V_{in}(n).T_s}{L} - \frac{V_o(1-d(n)).T_s}{L} \tag{7}$$

Rearranging (7), we have:

$$d(n) = \frac{L}{T}.\frac{i_L(n+1) - i_L(n)}{V_o} + \frac{V_o - V_{in}(n)}{V_o} \tag{8}$$

The duty cycle in each switching cycle could be calculated properly to achieve unity power factor. If AC-to-DC converter with PFC is designed properly, $i_L(n+1)$ is forced to follow the reference current, $i_{ref}(n+1)$, which is a rectified sinusoidal waveform, as shown in Fig. 3. V_o is controlled to follow the reference voltage, V_{ref}. Substituting $i_{ref}(n+1)$ and V_{ref} for $i_L(n+1)$ and V_o in (8) respectively, the duty cycle can be derived as a control strategy as follows:

$$d(n) = \frac{L}{T}.\frac{i_{ref}(n+1) - i_L(n)}{V_{ref}} + \frac{V_{ref} - V_{in}(n)}{V_{ref}} \tag{9}$$

where $i_L(n)$ is sensed by a resistor emulator and sampled by an Analog to Digital converter (A/D) current.

The duty cycle calculated by (9) can achieve unity power factor in a boost converter. Equation (9) can be rearranged as follows:

$$d(n) = d_1(n) + d_2(n) \tag{10}$$

where:

$$d_1(n) = \frac{(i_{ref}(n+1) - i_L(n)).\dfrac{L}{T_s}}{V_{ref}}, \tag{11}$$

$$d_2(n) = 1 - \frac{V_{in}(n)}{V_{ref}} \tag{12}$$

$d_1(n)$ is the current forcing component (CFC). In steady state, the inductor current, $i_L(n+1)$, follows the reference current, $i_{ref}(n+1)$, at the end of the switching cycle. Therefore, the numerator of (11) is the inductance times the derivative of inductor current in one switching cycle as: $V_L = L\dfrac{di_L(t)}{dt} = \dfrac{L}{T_s}[i_L(n+1) - i(n)]$. In transient state, $d_1(n)$ forces the inductor current to follow the reference current which is determined by the power balance between the input and output of the converter. $d_1(n)$ ensures the output voltage V_o, to be regulated to follow the reference voltage for transient state. In (7), the reference current is calculated by the following:

$$i_{ref}(n+1) = k_{PID}.\left|\sin(\omega_{line}.t(n+1)\right| \tag{13}$$

k_{PID} is the peak value of the reference current, which is the output of the voltage loop controller. $\left|\sin(\omega_{line}.t(n+1))\right|$ is the rectified line frequency sinusoidal waveform, which is stored as a look-up table. In the implementation, the input voltage could be sensed and processed to produce the unity rectified line frequency sinusoidal waveform. The advantage of using the look-up table to generate $\left|\sin(\omega_{line}.t(n+1))\right|$ is that the sinusoidal input current waveform can be achieved under non-sinusoidal input voltage conditions. The second component, $d_2(n)$, in (11) is determined by the input and output voltage equilibrium of the boost topology. Therefore, d_2 is defined as the Voltage Equilibrium Component (VEC). In (13), $V_{in}(n)$ is the instantaneous input voltage value sensed by the input voltage fed-forward channel, as shown in Fig. 4. $d_2(n)$ can guarantee stability of V_o for input voltage variations.

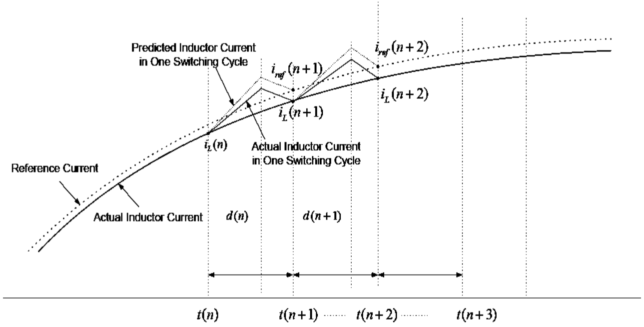

Fig. 5 Inductor current controlled by directly calculated duty cycles

Now, by substituting (13) into (9), the proposed PFC control algorithm can be expressed by the following equation:

$$d(n) = \frac{k_{PID}.\left|\sin(\omega_{line}.t(n+1))\right| - i_L(n)}{K_C} + \frac{V_{ref} - V_{in}(n)}{V_{ref}} \tag{14}$$

where, $K_C = \dfrac{T_S V_{ref}}{L}$, is a constant which characterizes the inductor current fluctuation in one switching cycle when only the reference voltage is applied on the inductor. This constant is defined as intrinsic current slope constant in this paper. The duty cycle $d(n)$, in (9) is generated based on two principals: the actual inductor current, $i_L(n)$, which is sensed at the beginning of the present switching cycle $t(n)$, and the desired inductor current, $i_{ref}(n+1)$, which is the reference current value at the beginning of the next switching cycle, $t(n+1)$, as shown in Fig. 5. The inductor current is controlled by $d(n)$ to follow the reference current. At $t(n+1)$, the inductor current $i_L(n)$ may not be exactly the same as, but very close to the reference current $i_{ref}(n+1)$. Because the reference current is sinusoidal, the actual inductor current will also be sinusoidal to achieve unity power factor.

D. Simplification of the Proposed PFC Control Algorithm

In the digital implementation of the proposed duty cycle calculation algorithm, (10), (12) and (13) can be simplified by multiplying all the parameters with the constant K_C, as follows:

$$D(n) = D_1(n) + D_2(n) \tag{15}$$

$$D_1(n) = k_{PID}.\left|\sin(\omega_{line}.t(n+1))\right| - i_L(n) \tag{16}$$

$$D_2(n) = K_C - V'_{in}(n) \tag{17}$$

where, $D_1(n) = d_1(n).K_C$, $D_2(n) = d_2(n).K_C$, and $V'_{in}(n) = \dfrac{V_{in}(n)}{V_{ref}}.K_C = \dfrac{T_S}{L}V_{in}(n)$

It is observed from (15), (16) and (17) that, only one multiplication and three additions (subtractions) are required to implement the proposed duty cycle control algorithm. Now, the proposed PFC control algorithm is very simple, and a low cost digital signal processor, microprocessor or field programmable gate array (FPGA) can be used to implement the PFC, operating at a high switching frequency.

5. Proposed Genetic Algorithm

In order to optimize the PFC, genetic algorithm (GA) which is based on natural evolution and population is implemented. This algorithm is usually used to reach a near global optimum solution. In each iteration of GA (referred as generation), a new set of string (.i.e. chromosomes) with improved fitness is produced using genetic operators (i.e. selection, crossover and mutation).

Chromosome's structure

Chromosome structure of a GA is shown in Fig. 6. This involves the K_p, and K_i as parameters of the controller.

B. Selection

The method of tournament selection is used for selections in a GA [24-25]. This method chooses each parent by choosing n_t (tournament size) players randomly, and choosing the best individual out of that set to be a parent. In this paper n_t is chosen as 4.

C. Cross Over

Cross over allows the genes from different parents to be combined in children by exchanging materials between two parents. Cross over function randomly selects a gene at the same coordinate from one of the two parents and assign it to the child. For each chromosome, a random number is selected. If this number is between 0.01 and 0.3 [25], the two parents are combined; else chromosome is transferred with no cross over.

D. Mutation

GA creates mutation children by randomly changing the genes of individual parents. In this paper, GA adds a random vector from a Gaussian distribution to the parents. For each chromosome, random number is selected. If this number is between 0.01 and 0.1 [25], mutation process is applied; else chromosome is transferred with no mutation.

E. Fitness Function

The fitness function is defined as in the following:

$$Fitness = Total\ Harmonic\ Distortion \qquad (18)$$

6. Simulation Results

Simulations for the system under study were performed in MATLAB Simulink environment. At first, the controller parameters of the PFC were optimized using the proposed GA. Performance evolution of the fitness function (best and average fitness in each iteration) is depicted in Fig. 7. The performance of the PFC controller in the harmonic elimination and current shaping is illustrated in Fig. 8. This figure shows the effectiveness of the proposed PFC scheme in elimination of harmonics and improvement of power quality. Next, the system is exposed to a sudden load change and the response is demonstrated in Fig. 9. These simulations validate the effectiveness of the proposed power factor scheme in harmonic elimination and power factor improvement, simultaneously.

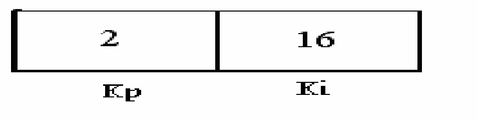

Fig 6: A typical chromosome

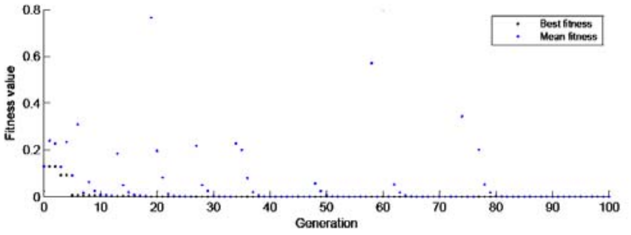

Fig 7: Performance evolution of fitness function (best and average fitnesses in every iteration)

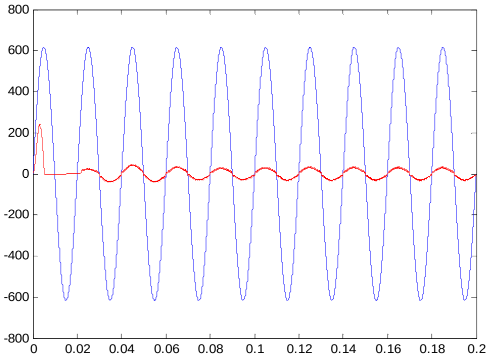

Fig.8: Voltage and current waveforms of micro-turbine after power factor correction

7. Conclusion

In this paper, a multi-function nonlinear link for distribution generation systems has been proposed. The main function of this link is to regulate the active power supplied from distribution generation to the utility. The link can also have the ability of supplying reactive power to the utility to operate in the unity power factor or to regulate the voltage at the PCC. This link can also be controlled to mitigate power quality problems. GA has been also used to optimize the performance of power factor correction controller. The effectiveness of the proposed power factor scheme in the harmonic elimination and the power factor improvement has been verified simulations performed in MATLAB/Simulink.

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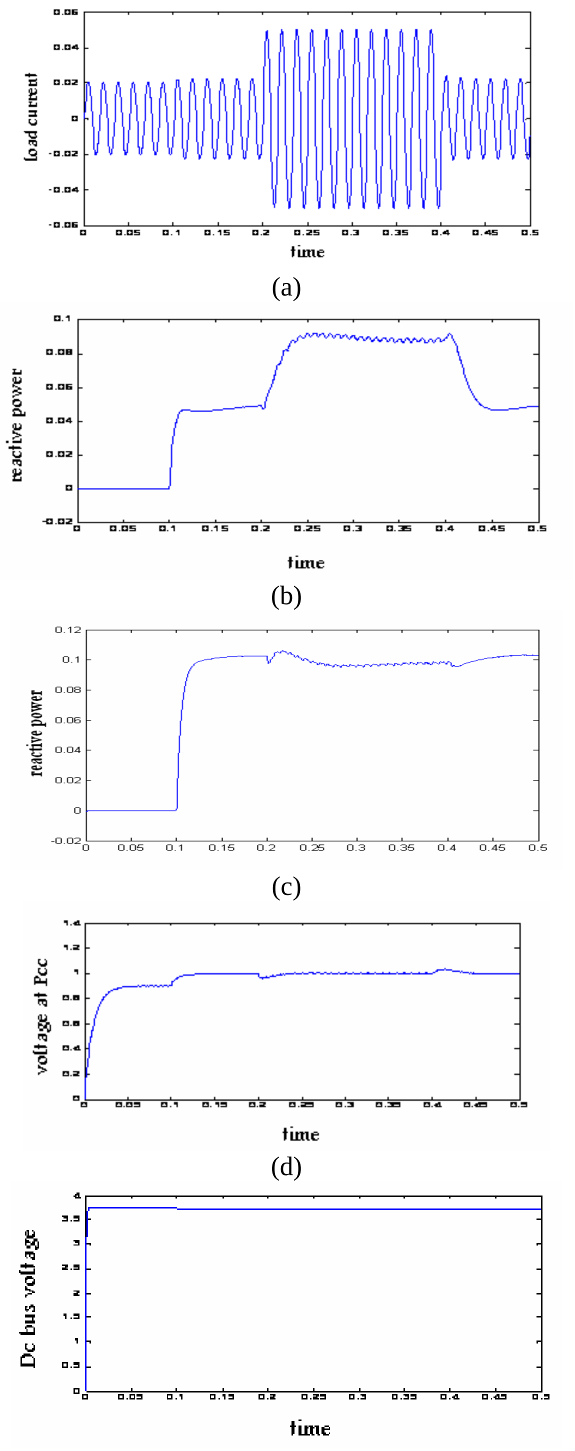

(a)

(b)

(c)

(d)

(e)

Fig. 9: Reactive power compensation corresponding to sudden load change. (a) Load Current (kA), (b) Compensated Mega Var, (c) Mega Watt supplied by the proposed configuration, (d) Voltage at PCC (per unit) and (e) DC-bus voltage (kV)