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Implementation of a 35KVA Converter Base on the 3-Phase 4-Wire STATCOMs for Medium Voltage Unbalanced Systems

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Abstract

This paper discussed a transformer-less shunt static synchronous compensator (STATCOM) with consideration of the following aspects: fast compensation of the reactive power, harmonic cancelation and reducing the unbalancing of the 3-phase source side currents. The STATCOM control algorithm is based on the theory of instantaneous reactive power (P-Q theory). A self charging technique is proposed to regulate the dc capacitor voltage at a desired level with the use of a PI controller. In order to regulate the DC link voltage, an off-line Genetic Algorithm (GA) is used to tune the coefficients of the PI controller. This algorithm arranged these coefficients while considering the importance of three factors in the DC link voltage response: overshoot, settling time and rising time. For this investigation, the entire system including the STATCOM, network, harmonics and unbalancing load are simulated in MATLAB/SIMULINK. After that, a 35KVA STATCOM laboratory setup test including two parallel converter modules is designed and the control algorithm is executed on a TMS320F2812 controller platform.

Key words: Back Static Synchronous Compensator (STATCOM), DSP, Genetic Algorithm (GA), Harmonic Distortion, Reactive Power, Total Harmonic Distortion, Unbalancing Load

I. INTRODUCTION

The widespread use of nonlinear loads such as variable speed drives, switched power supplies, rectifiers, and other industrial loads is known to generate harmonics and imbalances in network voltages and currents and also deterioration in the power quality of electrical systems [1]. Their presence in a network results in reduced efficiency, increases in the working temperature, and drastic reductions in the lifetime of the equipment of the power system. Passive filters like LC filters or capacitor banks have been used as a conventional solution to solve harmonic currents problems. However, they only filter the frequencies that they have been previously tuned for. Its operation cannot be limited to a certain load or group of loads. Resonance can occur due to the interaction between passive filters and others loads, with unexpected results. Therefore, using proper equipment on the level voltage of a distribution network in order to obtain a viable power quality in the electrical systems is essential. In this regard, compensation based on advanced power electronics as a solution to this problem is designed and implemented. The Shunt Active Filters are static synchronous compensators (STATCOM) connected in parallel with the load (Fig. 1.). They are capable of simultaneously compensating problems such as power factor, current imbalance and current harmonics and achieving a balanced sinusoidal current at the line, with a unitary value of the power factor. The principle of operation for the STATCOM is based on the generation and injection of harmonic current up to a desired order to the system. Consequently, a control algorithm is applied to calculate the load current harmonics and to eliminated them. A number of active filter configurations and control strategies have been proposed in the last two decades to achieve a desired harmonic compensation level [2]-[6].

All shunt active filters have controllers based on the instantaneous active and reactive power theory (p-q theory) [7] and pursue two major aims characterized by: 1. Sinusoidal line currents, independent of the harmonic of load currents. 2. Maintaining the average voltage of the capacitor at an acceptable constant value, which means that the fluctuating

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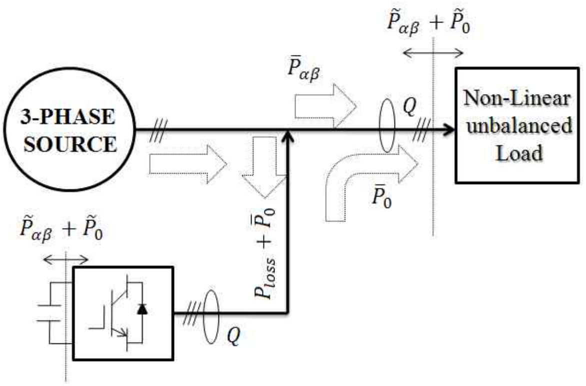

Fig. 1. Principle diagram of STATCOM control topology.

active power supplants between the DC link capacitor and load, and so that the STATCOMs do not need a power supply. In this paper a STATCOM based on the p-q theory has been studied. For obtaining higher power and for using STATCOMs in desired industrial loads, two transformer-less converters are designed and paralleled. Paralleling multiple converters for higher powers made the design, production, installation, and preservation much simpler and more flexible [8]. In addition, transformer-less converters can be directly connected to a medium-voltage network without a bulky step up transformer, resulting in cost and weight reductions [9]–[11].

In addition, the accuracy and time response of the control are very important to keep the volume and cost of the capacitor at an acceptable level. In fact, in transient operating conditions, avoiding a large transfer of energy to the capacitor, or from the capacitor, during one period of line voltage is a critical problem. To overcome this problem and to achieve a desirable dynamic robust control performance of the DC link voltage, the coefficients of a PI controller are determined by a genetic algorithm. Therefore, by selecting appropriate coefficients, a minimum DC link voltage overshoot can be obtained. In addition, with regard to the relation between the capacitor voltage and its volume, the minimum size of the system will be achieved. To accomplish these targets, first of all, the whole system is simulated in MATLAB/SIMULINK and then the control algorithm and the tuned PI are implemented on a TMS320F2812 DSP board.

II. PRINCIPLE OF OPERATION

A. Control Theory

As mentioned in the introduction, the control strategy is based on the instantaneous power theory extended for 3-phase four wire systems.

The p-q theory uses the $\alpha\beta0$ transformation, also known as the Clarke transformation, which transforms three phase voltages and current into the $\alpha\beta0$ stationary reference frames. The Clarke Transformation matrix is given below:

$$T = \sqrt{\frac{2}{3}}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{1}$$

By applying this transfer, the active and reactive powers with the zero-sequence power in the stationary reference frame can be expressed as:

$$P = v_\alpha i_\alpha + v_\beta i_\beta \tag{2}$$

$$Q = v_\beta i_\alpha - v_\alpha i_\beta \tag{3}$$

$$P_0 = v_0 i_0 \tag{4}$$

Where:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = T.\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = T.\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{6}$$

B. Control Theory

1) Positive Sequence Detector: For access to the desired control strategy, it is necessary to explain detection of the fundamental harmonic at the positive sequence voltage. By using a Phase Lock Loop (PLL) the basic frequency of the voltage can be obtained. In order to detect the frequency and phase angle and to generate the synchronizing signals to the switching logic, voltages network are fed to the PLL block [12]-[14]. Considering $i_{\alpha\beta1}$ as follows:

$$i_{\alpha1} = \sin(\omega t) \tag{7}$$

$$i_{\beta1} = \cos(\omega t) \tag{8}$$

Where ωt is the v_a-phase angle detected by the PLL block, and with the transferred measured voltages from equation (5) $v_{\alpha\beta}$, the active and reactive power can be calculated:

$$P_{\alpha\beta} = v_\alpha i_{\alpha1} + v_\beta i_{\beta1} \tag{9}$$

$$Q_{\alpha\beta} = v_\beta i_{\alpha1} - v_\alpha i_{\beta1} \tag{10}$$

These active and reactive powers have average and fluctuating values. Through a low pass filter, the average powers are extracted and then the fundamental harmonic of voltage can be calculated.

$$\begin{bmatrix} v_{\alpha1} \\ v_{\beta1} \end{bmatrix} = \frac{1}{i_{\alpha1}^2 + i_{\beta1}^2}\begin{bmatrix} i_{\alpha1} & i_{\beta1} \\ i_{\beta1} & -i_{\alpha1} \end{bmatrix}\begin{bmatrix} P_{ave} \\ q_{ave} \end{bmatrix} \tag{11}$$

With the inverse Clarke Transformation the positive sequence voltage in the basis frequency are obtained.

Using $v_{\alpha\beta 1}$ and the measured voltage and current values, both the negative and fluctuation components of the active power that should be supplied with a shunt active filter are calculated as follows:

$$P'_{\alpha\beta} = v_{\alpha 1} i_\alpha + v_{\beta 1} i_\beta - LPF(v_{\alpha 1} i_\alpha + v_{\beta 1} i_\beta) \tag{12}$$

Where LPF is an abbreviation for the Low Pass Filter.

This active power with other energy losses is supplied by the capacitor storage energy. Therefore, the DC link voltage of the capacitors drops and should be compensated with a DC link regulator. The total load reactive power can be given by:

$$Q = v_\alpha i_\beta - v_\beta i_\alpha \tag{13}$$

Now it is possible to determine the reference currents that should be generated by the compensator in the $\alpha\beta 0$ coordinates:

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} P'_{\alpha\beta} - P_{reg} \\ Q \end{bmatrix} \tag{14}$$

$$i^*_{c0} = i_0 = \frac{1}{\sqrt{3}}(i_a + i_b + i_c) \tag{15}$$

In equation (14), P_{reg} comes from the DC voltage regulator.

2) Regulation of the DC link voltage and the Genetic Algorithm: In the control strategy there is a component, P_{reg}, which is used to regulated the capacitor voltage in the DC link of the compensator. This regulation is done with a proportional integrator controller with an error between the reference voltage and the voltage at the terminal of the capacitors bank, V_{DC}.

$$P_{reg} = PI(V_{ref} - V_{DC}) \tag{16}$$

For the preservation of any overshoot on the voltage capacitors, selecting the PI coefficients is an important point. In this work, to tune the coefficients of the PI controller an off-line Genetic Algorithm (GA) is used**.** The GA is a computerized search and optimization method that works very similar to the principles of natural evolution. The GA's intelligent search procedure finds the best and fittest design solutions, which can be difficult to find using other techniques. By using a GA off-line procedure, the voltage DC link regulator coefficients (K_i, K_P) are determined. When an optimum set of coefficients with a minimized fitness function (FF) is reached, the search is terminated [15].The evolution of the fitness function in this case is made by weighting the transient overshoot value (OS), the rise time (t_r) and the steady state error (e_{ss}) and it is given as follows:

$$FF = K_0.OS + K_r.t_r + K_s.e_{ss} \tag{17}$$

Where K_0, K_r and K_s can be selected according to the importance of the three factors for the dynamic system response.

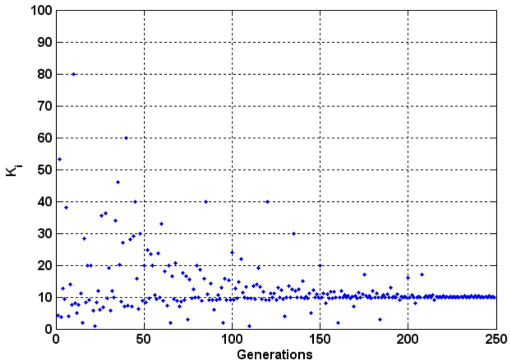

Fig. 2. process of GA for selecting k_i.

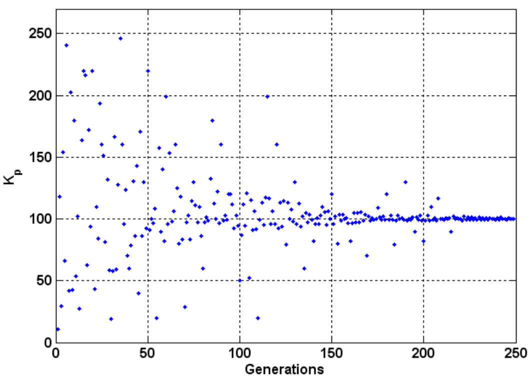

Fig. 3. process of GA for selecting K_P.

III. SIMULATION RESULTS

In this paper, the overall compensator system with the applied closed loop control is simulated in MATLAB/SIMULINK. As mentioned above, for the regulation of the PI coefficient, an off-line genetic algorithm is applied in MATLAB where $K_0 = 0.7$, $K_r = 0.1$ and $K_s = 0.2$ in per-unit, are selected (equation (17)).

Fig. 2 and Fig. 3 show the process used by the GA for selecting K_i and K_P. After the 250^{th} generation, K_i and K_P converge to 10.2 and 102.4, respectively.

These values are achieved when the DC link voltage command is 640-V, and the load is unbalanced (35%) and nonlinear (THD=30%). Fig.4. shows the capacitor DC link voltage. According to this figure, the DC voltage link has a minimum overshoot and therefore it is feasible to select capacitors with a minimum voltage for the DC link voltage. Fig. 5 and Fig. 6 show the network currents and compensator currents respectively before and after compensation. In this examination, a 3-phase unbalanced, nonlinear load is consideration to demonstrate the power of the designed 4-wire 3-phase STATCOM in terms of balancing currents and harmonic elimination inside of the network.

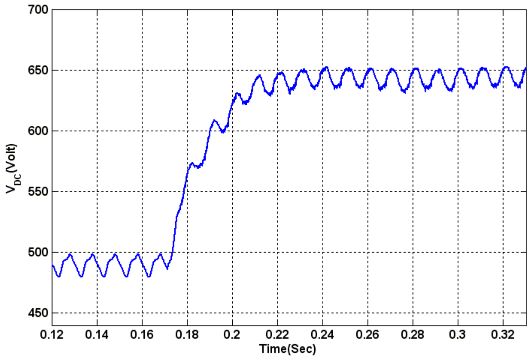

Fig. 4. DC link voltage curve by applying K_i, K_P which are selected with GA algorithm.

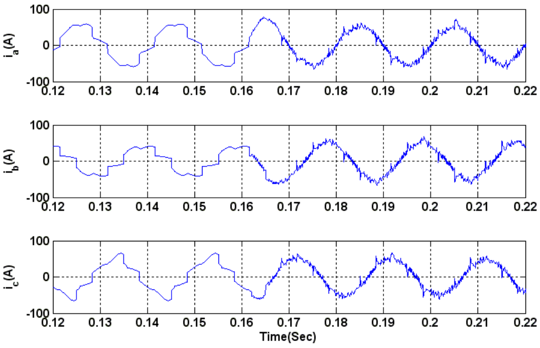

Fig. 5. Network currents before and after compensation.

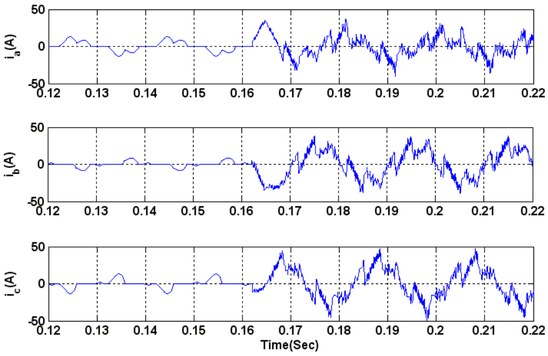

Fig. 6. Converter currents before and after compensation.

TABLE I.

PARAMETER AND CONSTANTS USED FOR THE LABORATORY SETUP TABLE TYPE STYLES

Parameter	Notation	Value
Line Voltage	V_{LL}	400V
Fundamental Frequency	F_0	50Hz
DC Link Voltage	V_{DC}	640V
Switching Frequency	F_{sw}	12kHz
Coefficients of DC Link PI controller	K_P / K_i	100/10

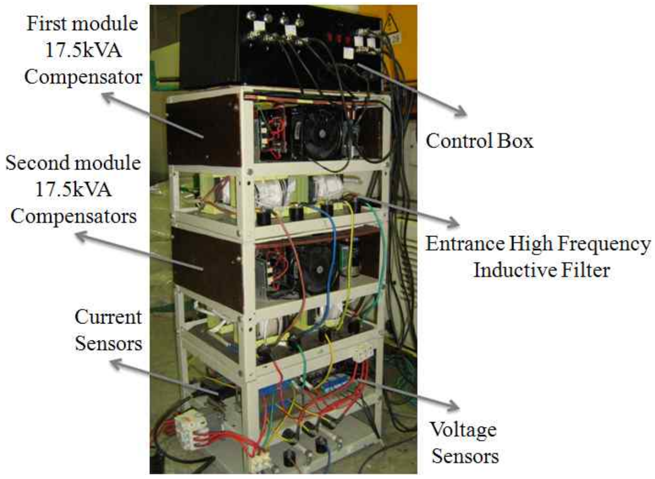

Fig. 7. Picture of the laboratory setup topology.

Based on the simulation results, the THD and the unbalancing are reduced to 0.4 and 0.5, respectively. By compensating the reactive power of the load, the power factor of the network will achieve unity.

IV. EXPERIMENTAL RESULTS

In order to evaluate the proposed STATCOM, its validity and its performance a laboratory test setup composed of two 4-leg 2-level inverters rated as 400V and 17.5KVA each, are made and implemented. This setup is shown in Fig.7. The parameter values and coefficients of the PI controllers and the power circuit features are given in tables I and II, respectively.

The overall control algorithm including the reference current estimator, legs current controller, capacitors voltage regulator, all based on the theory of instantaneous reactive power are executed on a TMS320F2812 board by C-language with Code Composer Studio 3.3 software. A block diagram of the proposed scheme is shown in Fig.8.

To prepare the sensors signal to contain network voltages, the load currents and the transmission to 12-bit A/D DSP kit, an analog interface circuit is designed. Fig.8 shows the designed control box.

Here three sets of experiments were performed:

a. Compensating a pure reactive current into the network by applying a 100HP 3-phase ac induction motor as a load.
b. Reduction of the network harmonics created from a 3-phase rectifier with an RL load as a nonlinear load.
c. Balancing of the network currents generated by a 3-phase imbalanced salt load. This load is made from three plates floating in salt water.

Case a: a three phase, 50-Hz, 400-V supply voltage is applied to an induction motor with a consumption of

35kVAR reactive power. The data recorded by the power analyzer are given in Table III. These data obviously show the high ability of the STATCOM in the compensation of reactive power.

Case b: a three phase, 50-Hz, 400-V supply voltage is applied to a three phase rectifier for examination of a nonlinear 1.4KW load. The waveforms of the network currents (THD=25.5) before the compensation are shown in Fig.10. The source currents obtained after the compensation for 4.5% current THD and converter currents are show in Fig.11 and Fig.12.

TABLE I.

POWER CIRCUIT FEATURES

Nominal Reactive Power	35Kvar
DC Link Capacitor	2(450v-1200 μF)
Inductance	3.14mH,50A
Switches	Mosfet,900v-100A
Drivers	ICL7667& SKH

TABLE II.

DATA RECORDED BY POWER ANALYZER

	Active power	Reactive power	Current network	Power factor
Before compensation	5.7KW	34.2KVAR	47.3A	16%
After compensation	6.01KW	0.5KVAR	10.5A	97.5%

Case c: a three phase, 50-Hz, 400-V supply voltage is applied to a three phase unbalanced salt load. The waveforms of the network currents before the compensation (30% unbalancing) are shown in Fig.13. After the compensation it is observed that the three phase source current is balanced and nearly sinusoidal. Fig.14 and Fig.15 show the experimental waveforms of the network currents and the converter currents after compensation with 5% unbalancing.

V. CONCLUSIONS

In this paper a 3-phase, 4-wire 35kVA STATCOM setup test with following features was presented:

- For supporting higher power nonlinear industrial loads and directly connecting to a medium-voltage network without a bulky step up transformer, two transformer-less converters were designed and paralleled.

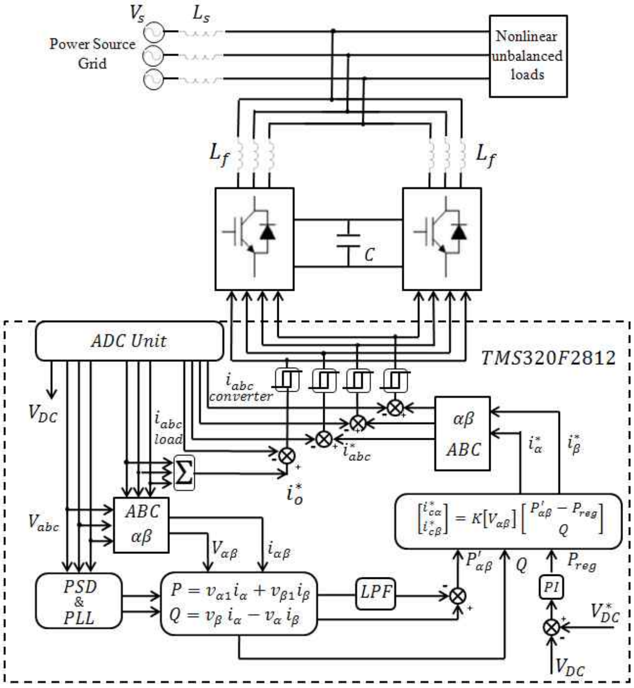

Fig. 8. Block diagram of the proposed scheme.

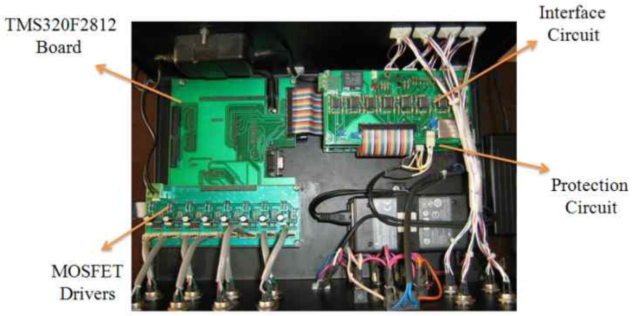

Fig. 9. Designed control box.

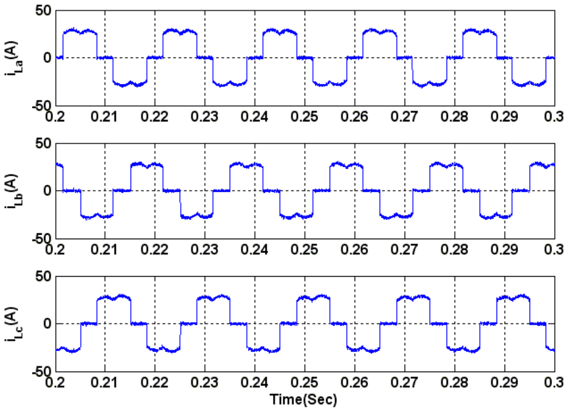

Fig. 10. Experimental waveforms of the nonlinear load with a current THD of 25.81%.

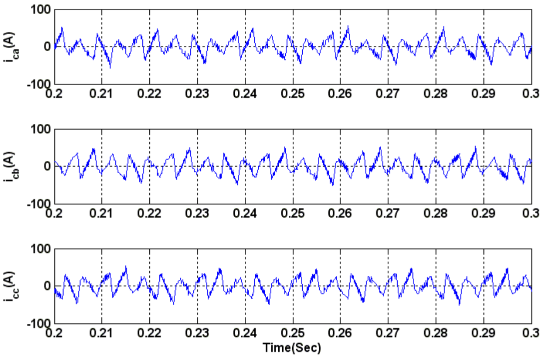

Fig. 11. Experimental waveforms of converter currents for harmonic test.

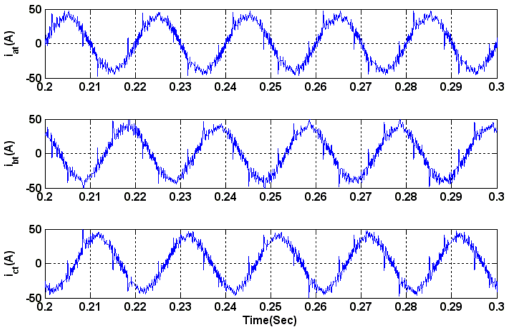

Fig.12. Experimental waveforms of network currents after compensation with THD=4.5%.

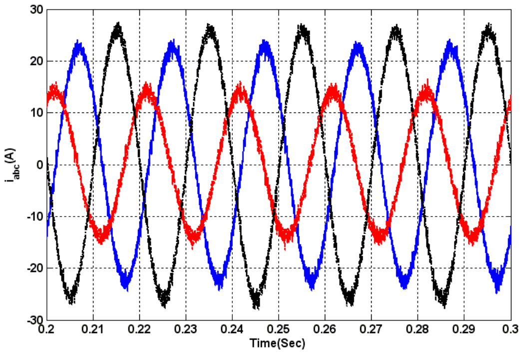

Fig. 13. Experimental waveforms of network currents before compensation with 30% unbalancing.

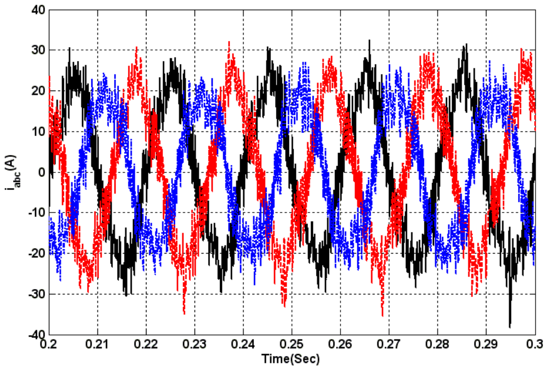

Fig. 14. Experimental waveforms of network currents after compensation with 5% unbalancing.

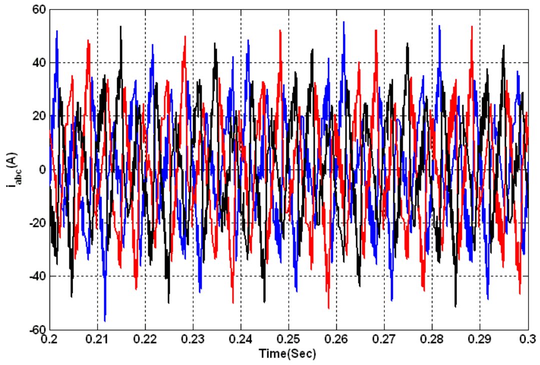

Fig.15. Experimental waveforms of converter currents for unbalancing test.

- For achieving a desirable dynamic robust control performance of the DC link voltage and to minimize the size of the capacitors and therefore the whole of the system, the control algorithm was optimized through coefficient selection of the PI controller by a genetic algorithm, and the system was adapted with the daily demand for compact utility.

Simulation and experimental results are utilized to verify the performance of this 35KVA STATCOM laboratory setup test including two parallel converter modules that were designed for distribution systems. The performance of the proposed system was satisfactory in terms of nonlinear and imbalanced loads and reactive power compensation.

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