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Automatic Power Factor Correction Using a Modified Statcom as a Continuously Controlled Capacitive Static VAR Compensator

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Abstract – *In this paper an automatic power factor correction system based on a new vision to statcom concept is presented. The reactive component of the load current is supplied by a statcom built of a halt-bridge voltage source inverter feeding a reactor and shunted by two dc capacitors. The passive components and control scheme of this configuration are approached in such a manner that the devised statcom behaves as pure capacitive impedance. The control strategy is based on governing the statcom current by its modulation index, while the passive components are designed such that all harmonic current harmonics are suppressed by the statcom reactor. The modulation index is controlled linearly by a precision gain-controlled linear amplifier which is specifically designed for this compensator and directly controlled by the load reactive current component. Modeling and performance of the proposed system was verified on PSpice.* **Copyright © 2012 Praise Worthy Prize S.r.l. - All rights reserved.**

***Keywords**: Compensator, Power Factor, Power Quality, Reactive Power, Statcom*

Nomenclature

VSI	Voltage source inverter
CSI	Current source inverter
IGBT	Insulated gate bipolar transistor
X_1	The first IGBT
X_2	The second IGBT
L_1	The inductance of the series reactor
r_1	The resistance of the series reactor
C_1	The first dc capacitor
C_2	The second dc capacitor
V_{ac}	The ac supply voltage
V_m	ac voltage amplitude
ω	ac voltage angular frequency
V_{X1}	The triggering signal of X_1
V_{X2}	The triggering signal of X_2
V_{mod}	The modulating signal
V_S	The carrier signal
f_S	Frequency of the carrier signal
m	Modulation index
f	Frequency of the ac voltage
T_S	The time duration of the carrier signal
T_1	The conduction time of X_1
T_2	The conduction time of X_2
i_L	The instantaneous load current
I_m	Amplitude of load current
iac	The ac supply current
φ	The load power factor angle
I_L	The r.m.s value of the load current
i_C	The statcom instantaneous current
I_{MAX}	The statcom r.m.s reactive current rating
L	The inductance of the load impedance
R	The resistance of the load impedance
$C.T$	Current transformer
L_f	The self inductance of the carrier ripples filter
R_f	The self resistance of the carrier ripples filter
C_f	The capacitance of the carrier ripples filter
R_{CT}	A small resistor representing a current Transformer
V_{con}	The controlling signal of the gain-controlled amplifier

I. Introduction

Power factor (*p.f*) correction improves power quality through energy saving and decreasing of transmission losses. Reactive power compensators are the basic means employed in automatic power factor correction systems.

The traditional static VAR compensators employed in power factor correction systems are switched capacitor banks and Fixed- capacitors, thyristor-controlled reactors [1]-[6]. A compensator employing switched capacitors is characterized by stepping response [5], [6], while a compensator employing fixed-capacitor, thyristor controlled-reactor is characterized by continuous response, significant odd harmonic releasing, and high no load operating losses, thus it needs harmonic filtering [1]-[4]. Many techniques approached power factor improvement through visions different from traditional techniques [7]-[16]. One of these techniques is using the variable inductive filter in which the filter inductance is controlled by a stepping air gap [7]. DC-DC converters were used in power factor correction through the optimization of continuous and discrete operation of their output currents [8].

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Better power factor correction occurred through their discrete operation [8]. AC-DC converters are widely used in power factor correction systems [9]-[16]. They are reliable static VAR compensator and are usually denoted by statcoms. A statcom is either a voltage source inverter (VSI) shunted by a dc capacitor or a current source inverter (CSI) shunted by a dc reactor.

These compensators are usually employing force-commutated solid state switching devices which are characterized by fast response. Wide spectrum of harmonics associate the reactive power compensation handled by these compensators, since their reactive and active power exchange with the ac source are usually done through small series rectors.

Many techniques were employed to reduce statcom harmonics such as multilevel technologies which add more complexity and cost [11]-[14]. In this paper a single-phase automatic power factor correction system is built using a modified configuration of VSI-based statcom.

The devised statcom represents capacitive impedance which is linearly and continuously controlled, harmonic-free and having negligible no load operating losses and no real power exchange with the ac source.

II. The Modified Single-Phase Statcom

The proposed statcom is shown in Fig. 1. It is built of a single-phase half-bridge voltage source inverter formed by X_1, X_2, a series reactor ($L_1 r_1$), and two dc capacitors C_1 and C_2. L_1 and r_1 are the self inductance and resistance of the reactor.

The ac source voltage (vac) has amplitude of V_m, angular frequency of ω, and an r.m.s value of V_{ac}.

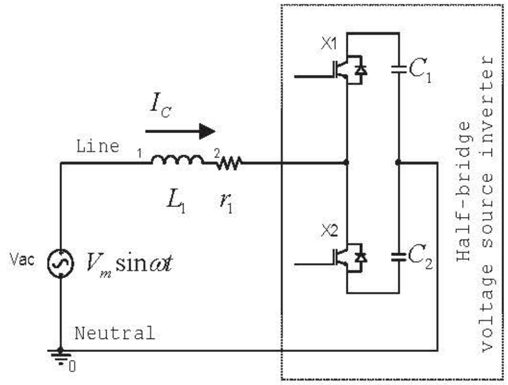


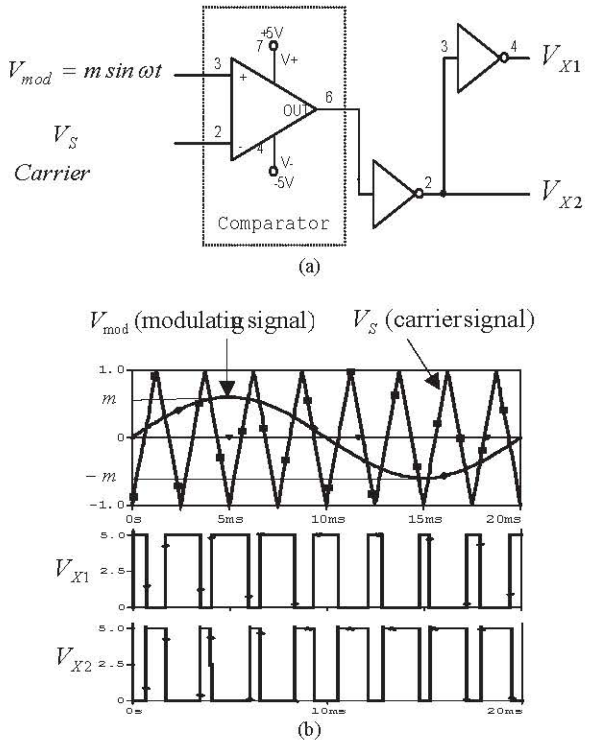
Fig. 1. The proposed statcom configuration

The capacitor C_1 will charge to $+V_m$ through L_1, r_1, and the embedded diode in the IGBT X_1, while the capacitor C_2 will charge to $-V_m$ through L_1, r_1, and the embedded diode in the IGBT X_2.

The switching devices X_1 and X_2 will be triggered by V_{X1} and V_{X2} respectively as shown in Fig. 2.

The triggering signals will be generated by comparing the modulating signal (V_{mod}) with a triangular signal (V_S) which has frequency of f_S. Note that V_{mod} is in phase with the ac source voltage vac. In Figs. 2, the parameter m is called the modulation index and is defined by:

$$m = \frac{Amplidude\ of\ V_{mod}}{Amplidude\ of\ V_S} \tag{1}$$



Figs. 2. The statcom sinusoidal pulse width modulation (SPWM) technique; (a) circuit and (b) waveforms

The conduction times of X_1 and X_2 at a certain ωt can be easily determined by examining Fig. 3. The triangular waveform frequency f_S is assumed very much greater than the modulating signal frequency f which is equal to $\omega/2\pi$, thus V_{mod} appears as a horizontal straight line in Fig. 3. T_S represents the time duration of the triangular waveform. If T_1 and T_2 are the conduction times of X_1 and X_2 respectively, then the following can be determined:

$$T_1 + T_2 = T_S \tag{2}$$

$$\begin{aligned} T_2 &= \frac{T_S}{2} - 2t'_1 = \\ &= \frac{T_S}{2} - 2\left(\frac{T_S}{4} m \sin\omega t\right) = \\ &= \frac{T_S}{2}\left(1 - m \sin\omega t\right) \end{aligned} \tag{3}$$

$$T_1 = T_S - T_2 = \frac{T_S}{2}\left(1 + m \sin\omega t\right) \tag{4}$$

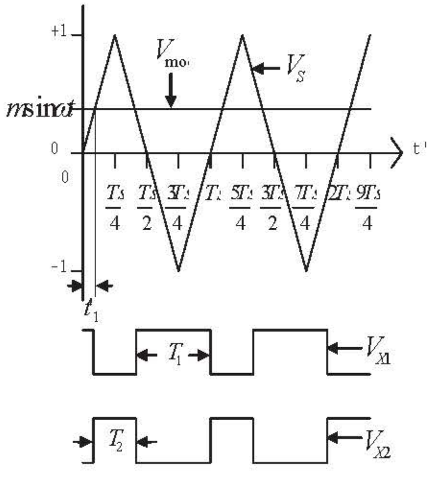


Fig. 3. X_1 and X_2 conduction times determination process

In the positive half cycle T_1 is greater than T_2 since *msinωt* is positive, whereas T_2 is greater than T_1 in the negative half cycle.

The average of the voltage generated by the voltage source inverter at any ωt is calculated as follows

$$V_i = \frac{1}{T_S}\left(\int_0^{T_1} V_m\,dt + \int_0^{T_2}\left(-V_m\right)dt\right) = \tag{5}$$
$$= \frac{1}{T_S}\left(V_m T_1 - V_m T_2\right) = mV_m \sin\omega t = mv_{ac}$$

At the ac source fundamental *f*, the proposed statcom can be modeled as shown in Fig. 4.

In this model, the half-bridge voltage source inverter is replaced by a sinusoidal voltage source of r.m.s value of mV_{ac} and an internal impedance of $1/\omega(C_1+C_2)$. For delivering pure sinusoidal capacitive current at the ac source frequency, the modified statcom in this paper is designed such that:

$$r_1^2 \ll \left(\frac{1}{\omega\left(C_1+C_2\right)} - \omega L_1\right)^2 \tag{6}$$

$$0.5 \le \omega^2\left(C_1+C_2\right)L_1 < 1 \tag{7}$$

The r.m.s value of statcom current (I_C) can be given by:

$$I_C = \frac{V_{ac} - mV_{ac}}{j\omega L_1 + \dfrac{1}{j\omega\left(C_1+C_2\right)}} = \tag{8}$$
$$= \left(1-m\right)I_{CMAX}\angle 90^0$$

where I_{CMAX} is the maximum r.m.s reactive current that can be delivered by this statcom and is defined by:

$$I_{CMAX} = \frac{V_{ac}}{\dfrac{1}{\omega\left(C_1+C_2\right)} - \omega L_1} \tag{9}$$

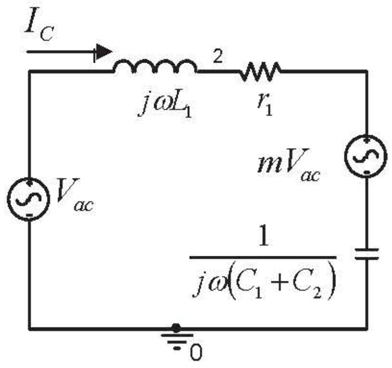


Fig. 4. The statcom model at the ac source fundamental

III. The Proposed Automatic Power Factor Correction System

Fig. 5 shows the layout of the modified statcom-based automatic power factor correction system.

In the controlling circuit, the ac source voltage is stepped down by a potential divider to a level that can be processed as an analogue input to a linear gain-controlled amplifier.

The load current is detected by the current transformer (C.T) and sampled at $\omega t = n\pi$ (n=1, 3, 5, …) to access a stepped down analogue voltage directly proportional to the load reactive current component.

The output of the amplifier represents the modulating signal V_{mod} which will be compared with a triangular waveform V_S of frequency of 2.5 kHz to generate the triggering signals V_{X1} and V_{X2}.

The instantaneous load current (i_L) can be given by:

$$i_L = \frac{V_m \sin\left(\omega t - \varphi\right)}{\sqrt{\left(\omega L\right)^2 + R^2}} = I_m \sin\left(\omega t - \varphi\right) \tag{10}$$

where φ and I_m represent the power factor angle and amplitude of i_L respectively and are defined by:

$$\varphi = \tan^{-1}\left(\frac{\omega L}{R}\right) \tag{11}$$

$$I_m = \frac{V_m}{\sqrt{\left(\omega L\right)^2 + R^2}} \tag{12}$$

The instantaneous statcom current (i_C) can be given by:

$$i_C = I_{CMAX}\left(1-m\right)\sin\left(\omega t + 90^0\right) \tag{13}$$

The load reactive current and the statcom current are out of phase.

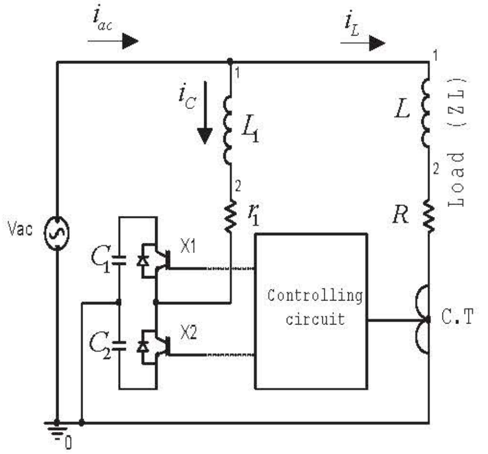


Fig. 5. The proposed automatic *p.f* correction system

They must be equal in magnitude so that they can cancel each other or it can be written:

$$I_m \sin\varphi = (1-m) I_{CMAX}, \quad \text{or } m = 1 - \frac{I_m \sin\varphi}{I_{CMAX}} \tag{14}$$

It is obvious that the modulation index m can be directly controlled by the load current reactive component. This type of control is completely different from the angle control scheme which is traditionally employed in statcoms [16]. A complete system designed on PSpice is shown in Fig. 6.

In the designing process of this system, necessary aiding literatures are invested [1], [17], [18]. All datasheets of electronic parts were taken into account and a power system of 220V, 50Hz is chosen as the ac source of the designed system.

The statcom passive elements shown in Fig. 5 were chosen according to (6) and (7) as follows: C_1=C_2=500μF, L_1=5.2mH, and r_1=0.104Ω. The reactor L_1r_1 in Fig. 5 is divided into two identical reactors of 2.6mH and 0.052 Ω each in Fig. 6. These identical reactors (L_1 and L_2) are connected in series and a series bandpass filter ($L_FR_FC_F$) tuned at f_S is inserted between the center point of them and the statcom common as shown in Fig. 6. The filter purifies the statatcom current i_C from the carrier ripples. The constraint governed by (7) makes L_1 suppress all the possible odd multiples of f, where the lowest of them (3rd harmonic) will at least be reduced to one fourth its value.

Since the above ac voltage source has amplitude of 311V, the statcom maximum rating I_{CMAX} is calculated to be 200A (peak value). This rating is sufficient for unity power factor correction for a load delivering a current of 250A (peak value) at 0.6 *p.f* lagging.

The small resistor R_{CT} in Fig. 6 represents a current transformer. Its voltage is sampled at ωt=nπ (n=1, 3, 5, …) and the resultant is an analogue voltage V_{con} which is proportional to the load reactive current component flowing in the load impedance L,R. V_{con} controls the gain-controlled amplifier which determines m.

IV. Results

The complete automatic power factor correction system was tested on PSpice at a temperature of 27C^0. Figs. 7 reflect the performance of this system at different loading conditions. Fig. 7(a) shows the compensation response for an inductive load of 250A (peak value) at a *p.f* of 0.6. The reactive component of that load was 200A inductive, thus the modified statcom generated its maximum capacitive current rating to correct the system *p.f* to unity. In Fig. 7(d), the statcom was relaxed since the load was pure resistive. All the four tests shows pure sinusoidal waveforms for the statcom current i_C and accurate performance since the compensator estimates exactly the load reactive current component within each cycle and releases the exact capacitive reactive demand that achieves unity power factor correction.

The statcom was separately tested on PSpice throughout the variation of the modulation index m from 0 to unity. m can be varied by varying V_{mod} with respect to V_S. The theoretical and the PSpice results of the statcom current were plotted against m as shown in Fig. 8. It is obvious that the theoretical results which were obtained by applying (8) are almost coinciding with PSpice results.

V. Conclusion

In this paper, a reliable and adaptive modification of statcom concept using half-bridge voltage source inverter is adopted. The results obtained from PSpice tests, have demonstrated the modeling validity of the modified statcom.

The new concept makes it possible to devise continuously and linearly controlled pure capacitive impedance at the ac source fundamental without harmonics generation and real power exchange with ac source.

This impedance offers the possibility of delta connections, thus it can be utilized in all three-phase applications requiring capacitive reactive power control for power quality purposes. The features of the adopted statcom compared to conventional ones are no real power exchange with ac network, no generation of harmonics, and wide zone of pure capacitive reactive power control.

The statcom adopted in this paper shows how a simple configuration approached in a new vision yields a striking results and become a diehard competitor to more complicated multilevel technologies

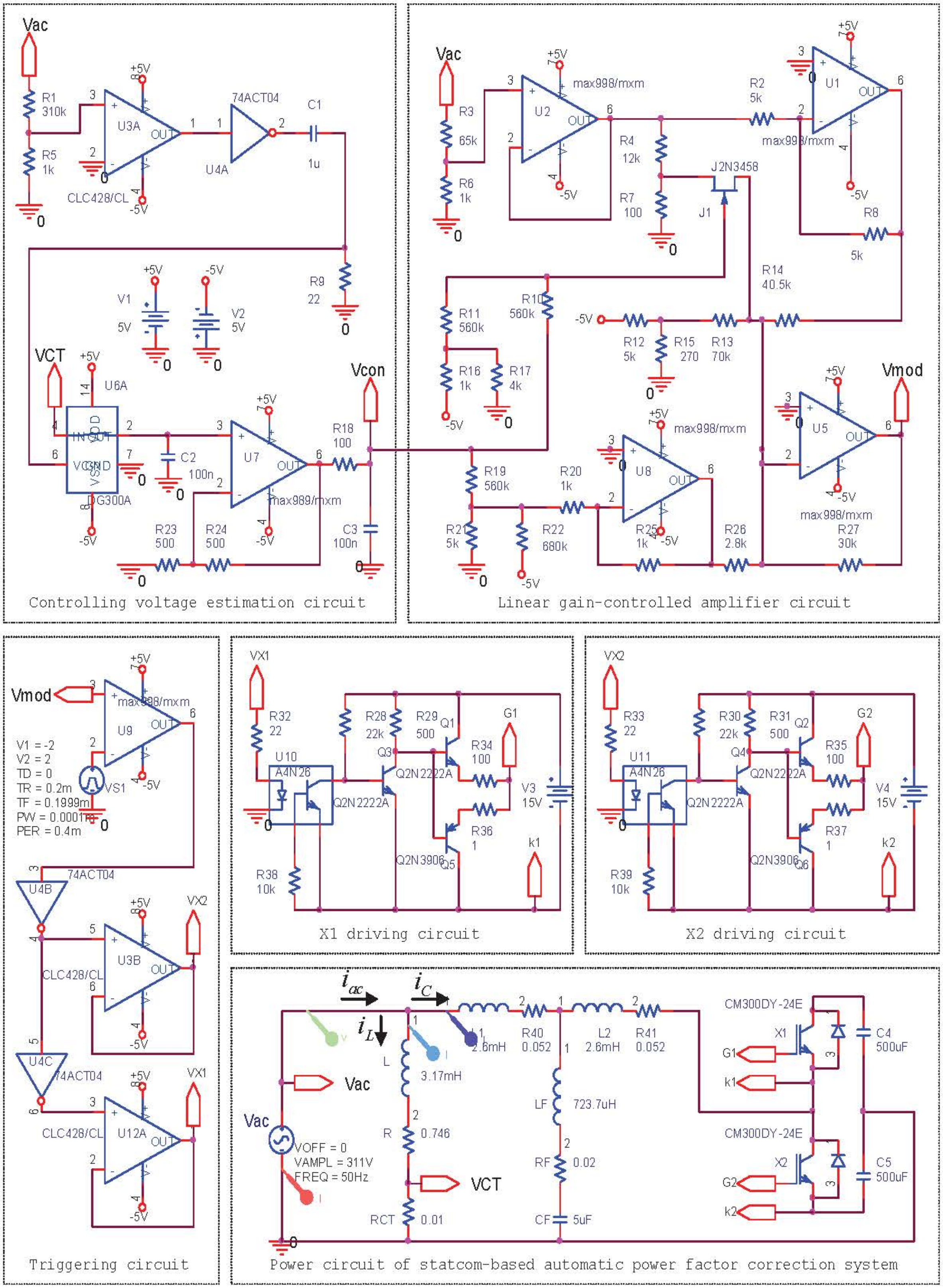
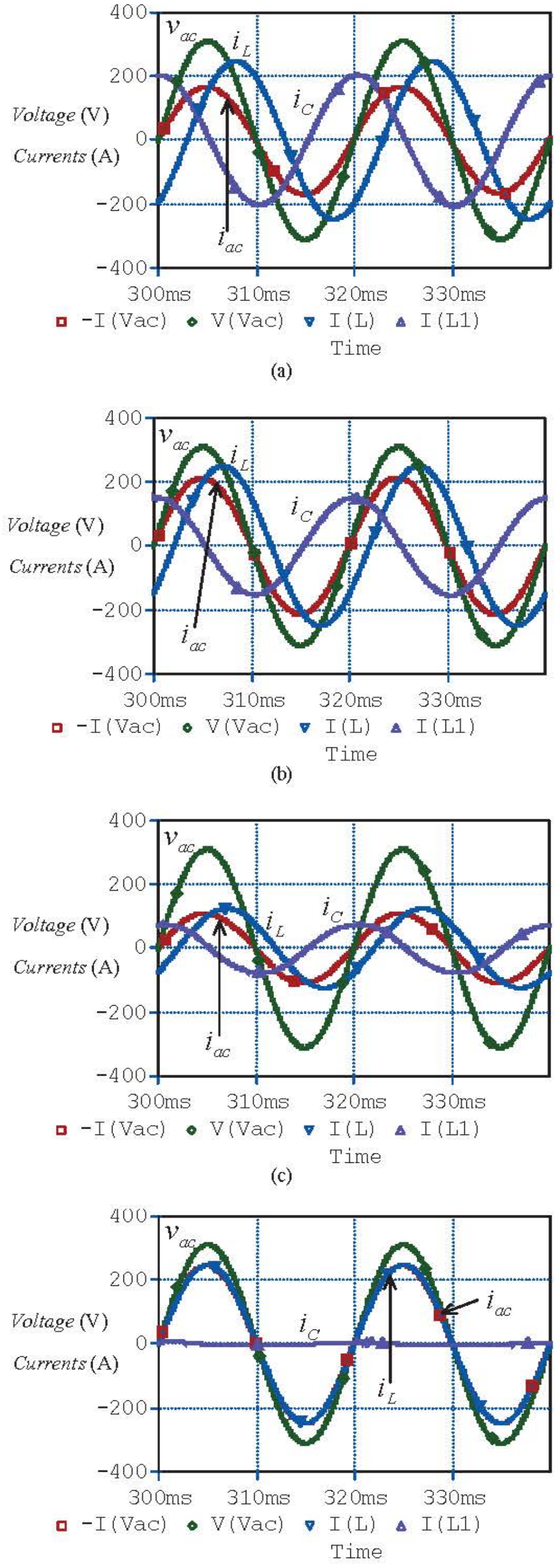


Fig. 6. The circuit diagram of the modified statcom-based automatic power factor correction system



(a)

(b)

(c)

(d)

Figs. 7. System response to inductive loads of; (a) 250A, 0.6 *p.f*, (b) 250A, 0.8 *p.f*, (c) 125A, 0.8 *p.f*, and (d) 250A resistive load

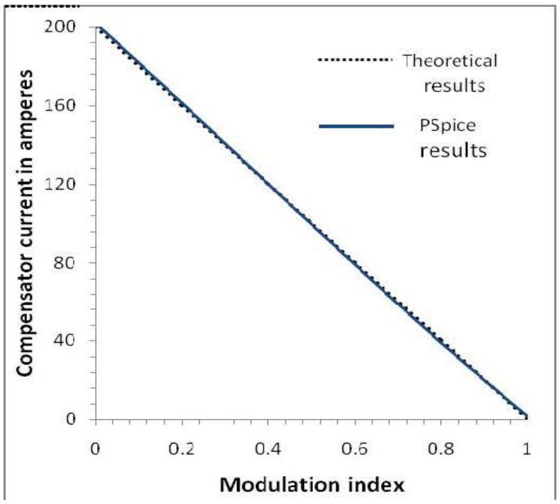


Fig. 8. Modified statcom current versus modulation index

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