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Design of a Statcom-Based Harmonic-Free Static VAR Compensator for Load Balancing Purposes

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In this paper, a bipolar (capacitive and inductive) static VAR compensator is built on the basis of statcom fundamentals. The designed compensator exchanges wide range of pure reactive power with the ac supply without significance of real power contribution. No harmonic generation is associating the compensation process, thus no filtering is required. The compensator is built of two single-phase statcoms connected in parallel. One of them represents a static linear synchronous condenser at the ac supply fundamental frequency, while the other represents a harmonic-free linearly and continuously controlled reactor. Each statcom is built of a half-bridge voltage source inverter shunted by two dc capacitors and exchanges pure reactive power with the ac supply through a series reactor. The reactive power of each statcom is controlled linearly by the modulation index of its voltage source inverter. A demonstration system for this compensator is designed and tested on PSpice.

Key words: Controlled reactor, Load balancing, Power quality, Statcom, Static VAR compensator

1. INTRODUCTION

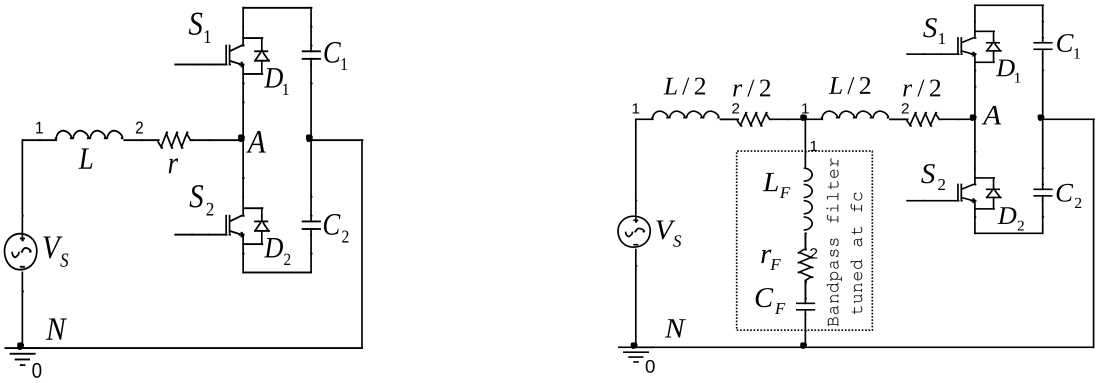
Load balancing requires continuous control of static VAR compensators in capacitive and inductive modes of operation (Chen, Lee and Chen 1999; Lee and Wu 2000; Valderrama, Mattavelli and Stankovic 2001; Xu et al. 2010). Synchronous condensers can be employed as continuously controlled reactive power compensators in balanced systems, but static VAR compensators are superior to them due their fast responses, low operating losses, and the possibility of being employed in applications requiring unbalanced reactive power control (Bimal 2006; Teleke et al. 2008). Conventional static VAR compensators constructed of fixed or switched capacitors and thyristor controlled reactors can be employed as bipolar (capacitive and inductive) reactive power compensators for load balancing purposes (Best and Zelaya-De La Parra1996; Gyugyi 1988; Lee and Wu 2000; Morbn, Ziogas and Joos 1993). Such kinds of compensators release disturbing harmonics and employ natural commutated medium speed switching devices (IEEE PES Harmonic Working Group 2001). Static compensators (statcoms) require forced commutation fast switching devices and have fast responses compared to conventional static VAR compensators. A statcom is either a voltage source converter loaded by a dc capacitor and exchange reactive power with the ac supply through a small reactor, or a current source converter loaded by a dc reactor (Bimal 2006; Tavakoli Bina and Hamill 2005).

Statcoms under the above definitions release wide spectrums of harmonics and exchange unnecessary real power with ac supplies (IEEE PES Harmonic Working Group 2001). Consequently, the above compensators usually require harmonics filtering circuitries installed together with them. Harmonics can also be minimized by employing multilevel statcoms which results in more complicated systems (Hadjeri, Ghezal and Zidi 2008). Harmonics minimization Techniques cause more no load operating losses.

In this study, a linearly and continuously controlled bipolar (capacitive and inductive) static VAR compensator built on the basis of single-phase statcom concept will be presented. The new configuration will be capable to exchange pure reactive power with the ac supply at its fundamental frequency without real power contribution or harmonics association. The compensator that will be devised requires no harmonics filtering and dissipates negligible no load operating losses.

2. THE PROPOSED SINGLE-PHASE STATCOM

The proposed single-phase statcom is shown in **Fig. 1a**. It is simply a single-phase half-bridge voltage source inverter loaded by two dc capacitors C_1 and C_2 and fed by the series reactor L. The resistor r represents the self resistance of the series reactor. The statcom configuration in **Fig. 1a** can be modified by dividing the series reactor L into two identical reactors and equipping the new configuration with a series bandpass filter as shown **Fig. 1b**. The filter is tuned at the carrier frequency f_C which represents the frequency of the triangular signal employed in the generation of the sinusoidal pulse width (SPWM) signals required for triggering the single-phase half-bridge voltage source inverter. This helps to smooth the envelope of the statcom current. The ac supply (vs) is a sinusoidal voltage having amplitude of V_m and angular frequency of ω. The bandpass filter is designed such that it draws negligible current from the ac supply.



(a) (b)

Fig. 1: The proposed statcom configurations: **(a)** simple and **(b)** modified.

In Fig. 1a, the capacitor C_1 will charge to $+V_m$ through the series reactor and the diode D_1, whereas C_2 will charge to $-V_m$. The insulated gate bipolar transistors (IGBTs) S_1 and S_2 are triggered by V_{S1} and V_{S2} respectively as shown in **Fig. 2a**. These signals are produced by comparing the modulating signal (v_{mod}) with the triangular signal (v_C). v_{mod} is a sinusoidal voltage proportional to v_S and in phase with it. If a parameter m is defined as the normalised amplitudes ratio of v_{mod} to v_C, then

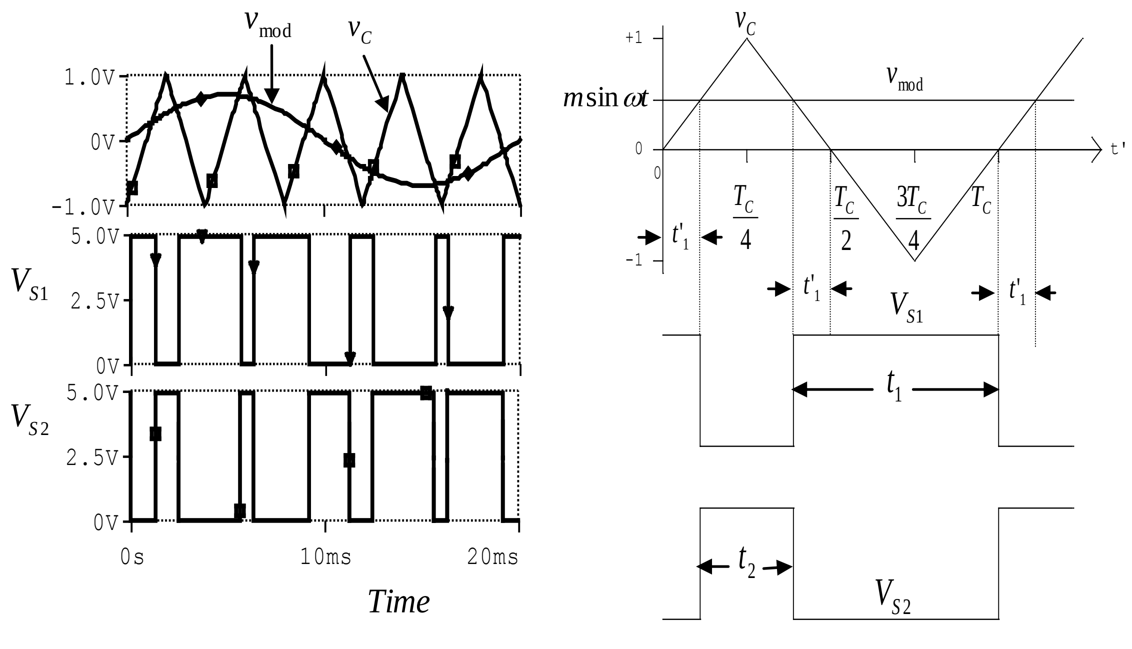
$$v_{\text{mod}} = m \sin \omega t \quad (1)$$

Here m represents the inverter modulation index. If the triangular signal frequency f_C is very much greater than the modulating signal frequency f which is equal to $\omega/2\pi$, then at any ωt, S_1 will conduct for a period of time of t_1, while S_2 will conduct for a period of time of t_2 as shown in **Fig. 2b**. The following can be deduced from this figure

$$t_1 + t_2 = T_C \quad (2)$$

$$\begin{aligned} t_2 &= \frac{T_C}{2} - 2t'_1 \\ &= \frac{T_C}{2} - 2\left(\frac{T_C}{4} m \sin \omega t\right) \quad (3) \\ &= \frac{T_C}{2}\left(1 - m \sin \omega t\right) \end{aligned}$$

$$t_1 = T_C - t_2 = \frac{T_C}{2}\left(1 + m \sin \omega t\right) \quad (4)$$



(a) (b)

Fig. 2: The statcom sinusoidal pulse width modulation (SPWM). **(a)** Switching devices triggering signals and **(b)** their conduction periods

If the term ($msin\omega t$) is positive, then t_1 is greater than t_2 and vice versa. The instantaneous voltage (v_i) generated by the inverter at any ωt, is shown in **Fig. 3**. The average of v_i at any ωt is designated by V_i and is calculated as follows

$$V_i = \frac{1}{T_C}\int_0^{T_C} v_i dt = \frac{1}{T_C}\left(\int_0^{t_1} V_m dt + \int_0^{t_2}(-V_m)dt\right) = \frac{1}{T_C}(V_m t_1 - V_m t_2) = mV_m \sin\omega t \qquad (5)$$

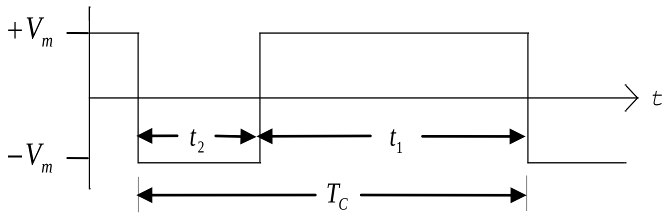


Fig. 3: The instantaneous voltage (*vi*) generated by the inverter at certain ωt.

The envelope scanned by V_i from 0 to 2π, represents the inverter voltage fundamental (v_1) which is synchronized with the ac supply instantaneous voltage v_S and running at the supply fundamental frequency *f*. The difference between v_i and v_1 is the source of all current harmonics, thus the circuit of **Fig. 1a** can be modelled as shown in **Fig. 4a**. The capacitance C_T represents $C_1//C_2$.The current source i_H includes all the possible harmonic current components starting from the odd multiples of the ac supply fundamental *f* and ending with the multiples of the carrier frequency f_C. The current source i_1 is a pure capacitive current at the ac supply fundamental *f* and is given by

$$i_1 = mV_m \omega C_T \sin(\omega t + \pi/2) \qquad (6)$$

The statcom approached in this paper is designed such that

$$\left(\frac{1}{\omega C_T} - \omega L\right)^2 >> r^2 \qquad (7)$$

$$0.5 \le \omega^2 C_T L \qquad (8)$$

The constraint defined by (7) guaranties pure reactive current at the ac fundamental, while the constraint defined by (8) makes L suppress all components of i_H starting from third harmonic. Consequently, the statcom modeling of **Fig.4a** can be simplified as shown in **Fig. 4b**.

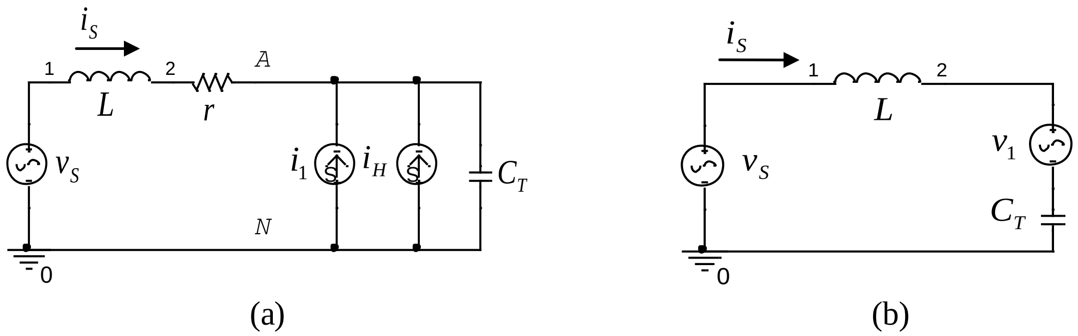


Fig. 4: The proposed single-phase statcom modeling: **(a)** exact and **(b)** simplified

The statcom impedance (Z_S) is given by

$$Z_S = \left|\omega L - 1/\omega C_T\right| \angle\varphi \qquad (9)$$

Where, φ is the impedance angle. If it is +90^0, then the statcom current i_S will be pure inductive, whereas for φ=-90^0, i_S will be pure capacitive. The current i_S can be given by

$$i_S = \frac{v_S - v_1}{Z_S} = \frac{V_m \sin\omega t - mV_m \sin\omega t}{\left|\omega L - 1/\omega C_T\right|\angle\varphi} = \frac{(1-m)V_m \sin(\omega t - \varphi)}{\left|\omega L - 1/\omega C_T\right|} \qquad (10)$$

The statcom current can be linearly varied from zero to its maximum value by varying the modulation index m from unity to zero.

3. THE PROPOSED BIPOLAR STATIC VAR COMPENSATOR

Two statcoms of **Fig. 1a** are connected in parallel as shown in **Fig. 5**, to build a single-phase static VAR compensator controllable linearly and continuously in capacitive and inductive modes of operation. The left statcom formed by L_1, S_1, S_2, C_1, *and* C_2 is designed such that it can draw pure capacitive current from v_S, while the right statcom is designed to draw pure inductive current. Each of the reactors L_1 and L_2 must be divided into two identical reactors as in **Fig. 1b**. Both statcoms must comply with the constraints specified by (7) and (8) and must be capable of handling the same maximum reactive currents. Consequently, it can be written

$$\frac{V_m}{1/\omega(C_1 + C_2) - \omega L_1} = \frac{V_m}{\omega L_2 - 1/\omega(C_3 + C_4)} \qquad (11)$$

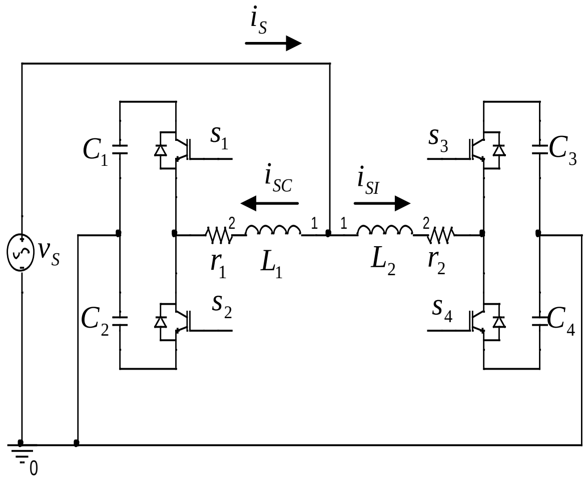


Fig. 5: The proposed single-phase statcom-based static VAR compensator

If the reactive current demand is capacitive, then the switching devices S_1 and S_2 will be activated, whereas S_3 and S_4 will be off. Therefore the left statcom will draw pure capacitive current (i_{SC}) proportional to the reactive current demand. In case of inductive reactive current demand, the left statcom will be relaxed and the right statcom will satisfy the demand by drawing pure inductive current (i_{SI}).

4. COMPENSATOR CIRCUIT DESIGN

A single-phase power system of 220V (RMS value) and 50Hz was chosen as the ac supply v_S of the proposed compensator. The amplitude V_m of the system voltage is 311V. The compensator is designed such it can handle maximum peak reactive current of 200A for capacitive and inductive modes of operation. The reactors L_1 and L_2 were chosen to have resistance to inductance ratio of 0.01(Ω/mH). Choosing $\omega^2 L_1(C_1+C_2)$ =0.51 and applying (11), the following basic design parameters were obtained: $C_1=C_2$=500µF, L_1=5.2mH, $C_3=C_4$=1000µF, and L_2=10mH. A complete system was designed on the computer program PSpice using aiding literatures (Bimal 2006; Miller 1982; Skvarenina 2002) and datasheets of electronic parts employed in electronic circuitries. The circuit diagram of the designed compensator is shown in **Fig. 6**. Each of the reactors L_1 and L_2 of **Fig. 5** are divided into two identical reactors in **Fig. 6**. A triangular waveform of amplitude of 2V and f_C of 2.5 KHz was chosen as the carrier of the SPWM circuit. The compensator was equipped with two bandpass filters having the parameters L_F=723.7µH, r_F=0.02Ω, and C_F=5µF. The controlling voltage of this system is the voltage V_d which is proportional to the reactive current demand. The range of V_d is -4V to +4V. Its negative sign means that the reactive current demand is inductive, while positive sign means capacitive current demand. The polarity of this voltage (V_P) will be invested in the triggering circuit to determine which statcom should be activated, whereas its absolute value (V_a) will determine the output voltage v_{mod} of the linear gain-controlled amplifier which was designed by investing the most linear portion of the characteristics of a fast junction field effect transistor. The amplitude of v_{mod} can be controlled linearly from zero to 2V by varying V_a from 0 to 4V. Consequently, the modulation index m of the activated statcom can be varied linearly from unity to zero as the absolute of V_d varies from 0 to 4V.

5. RESULTS AND DISCUSSION

The compensator was tested on PSpice for zero reactive current demand. **Fig. 7a** shows the results of that test which corresponded to V_d=0 and m=1. Many tests were preceded during reactive current demand variations from 0 to compensator maximum rating (200A peak value) in capacitive and inductive modes of operation. In **Fig. 7b**, the measured values of the compensator current are plotted against reactive current demand in capacitive and inductive modes of operation. This figure obviously reflects the linearity of the proposed compensator. Note that the minus sign of current in **Fig. 7b** means inductive, while positive sign means capacitive.

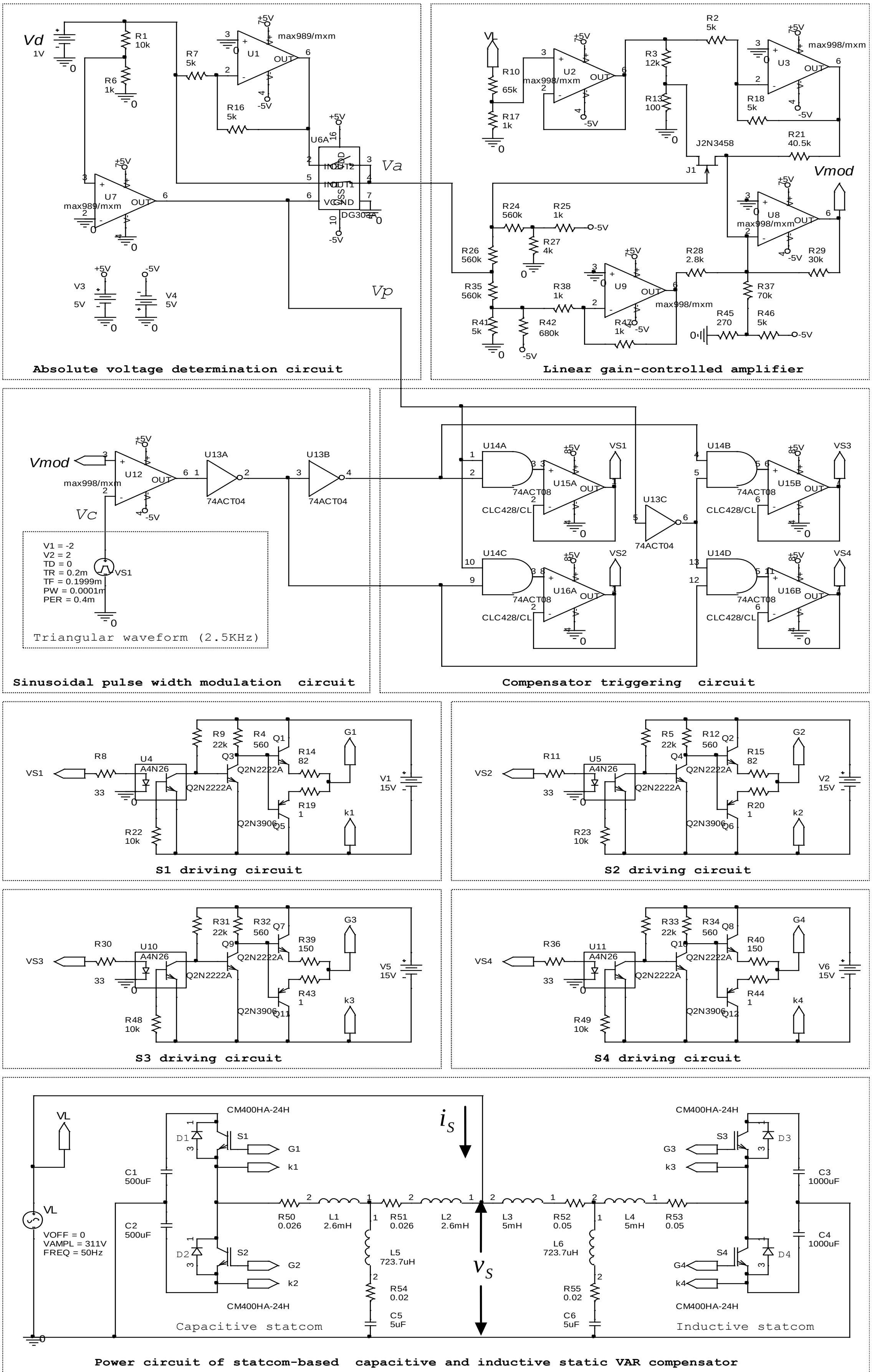
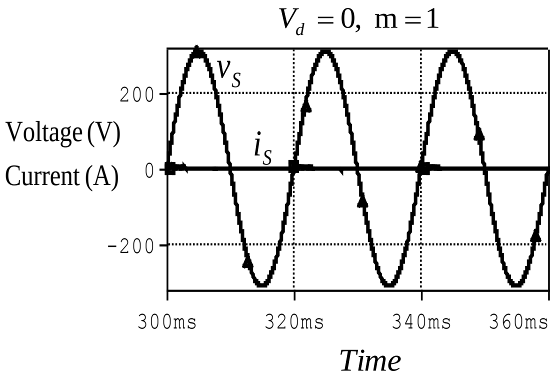
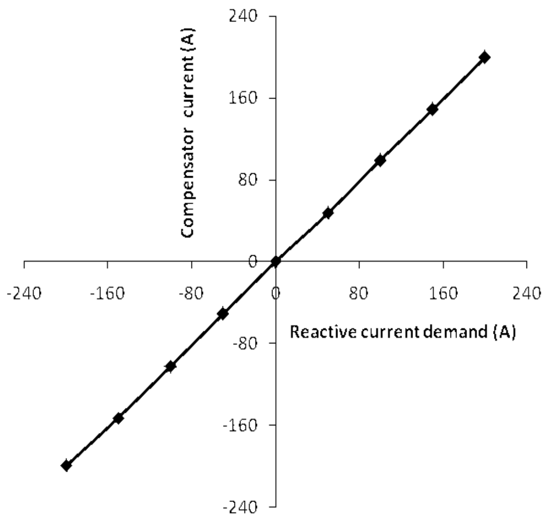


Fig. 6: PSpice design of statcom-based bipolar (capacitive and inductive) static VAR compensator



(a)



(b)

Fig. 7: Compensator response to: **(a)** zero reactive current demand and **(b)** reactive current demand variations of -200A to +200A (peak values).

The compensator instantaneous voltage v_S and current i_S in capacitive and inductive modes of operation are shown in **Fig. 8a** and **Fig. 8b** respectively. It is obvious that absolute values of the voltage V_d in **Fig. 6**, control the modulation index *m* which determines the absolute value of the compensator current, while the polarity of V_d determines the compensator current phase angle φ which is $+90^0$ for positive sign and -90^0 for negative sign.

6. CONCLUSION

In this paper, a bipolar (capacitive and inductive) static VAR compensator is designed on the basis of statcom concept. The current of this compensator is pure reactive and its waveform is pure sinusoid running at the ac supply fundamental frequency without any sort of harmonics association and real power contribution. The configuration and the control strategy adopted in this paper, present satisfactory replacements of technologies requiring the building of multilevel converters and high power harmonic filters. The proposed compensator can be represented by a bipolar linear susceptance that offers the possibility of delta connection which can be employed in load balancing techniques. Overall, the proposed compensator can be considered as a parallel combination of static synchronous condenser and reactor having equivalent reactive ratings and offering the possibility of wide zone of linear and continuous control.

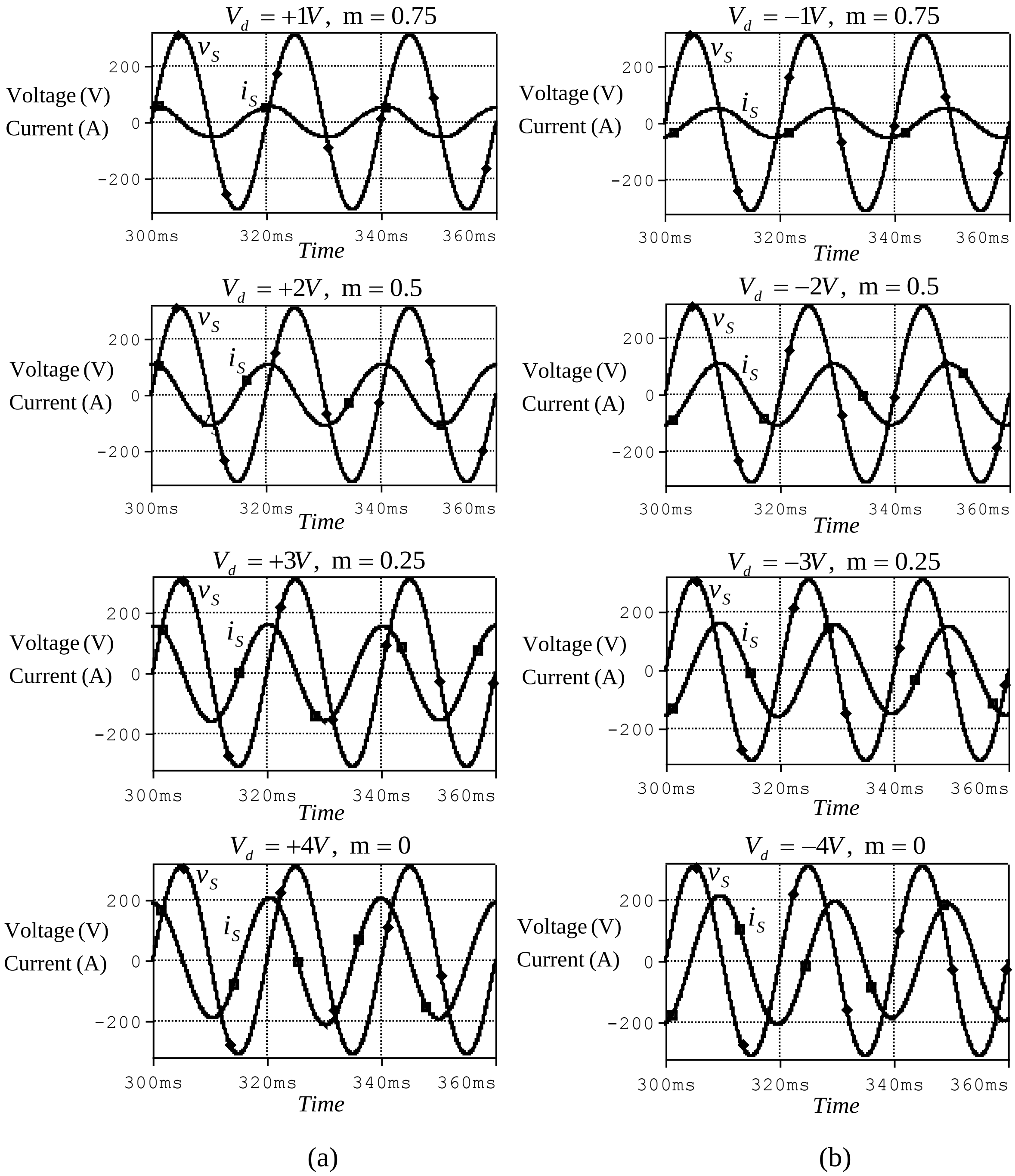


Fig. 8: The compensator voltage and current waveforms in: **(a)** capacitive mode and **(b)** inductive mode of operation.

REFERENCES

Best R, Zelaya-De La Parra H (1996). Transient Response of a Static Var Shunt Compensator. IEEE Transaction on Power Electronics, 11: 489-494.

Bimal K.B **(**2006). Power Electronics and Motor Drives. Elsevier Inc, USA.

Chen J-H, Lee W-J, Chen, M-S (1999). Using a Static Var Compensator to Balance a Distribution System. IEEE Transaction on Industry Applications, 35: 298-304.

Gyugyi L (1988). Power Electronics in Electric Utilities: Static Var Compensators. Proceeding of the IEEE, 76: 483-494.

Hadjeri S, Ghezal F, Zidi S.A (2008). Simulation of a Three-Level-48 Pulses STATCOM. ACTA Electrotehnica, 49: 189-193.

IEEE PES Harmonic Working Group (2001). Characteristics and Modeling of Harmonic Sources—Power Electronic Devices. IEEE Transactions on Power Delivery, 16: 791-800.

Lee S-Y, Wu C-J (2000). Reactive Power Compensation and Load Balancing for Unbalanced Three-Phase Four Wire System by a Combined System of an SVC and a Series Active Filter. IEE Proc.-Elccrr. Power Appl., 147: 563-571.

Miller T.J (1982). Reactive Power Control in Electric Systems. John Willey & Sons, Toronto.

Morbn L, Ziogas P.D, Joos, G (1993). A Solid-State High-Performance Reactive Power Compensator. IEEE Transaction on Industry Applications, 29: 969-978.

Skvarenina T (2002). The Power Electronics Handbook. CRC Press, Florida.

Tavakoli Bina M, Hamill D.C (2005). Average Circuit Model for Angle-Controlled STATCOM. IEE Proc.-Electr. Power Appl., 152: 653-659.

Teleke S, Abdulahovic T, Thiringer T, Svensson J (2008). Dynamic Performance Comparison of Synchronous Condenser and SVC. IEEE Transaction on Power Delivery, 23: 1606-1612.

Valderrama G.E, Mattavelli P, Stankovic A.M (2001). Reactive Power and Unbalance Compensation Using STATCOM with Dissipativity-Based Control. IEEE Transaction on Control systems Technology, 9: 718-727.

Xu Y, Robert, L.M, Kueck J.D, Rizy, D.T (2010) Voltage and Current Unbalance Compensation Using a Static Var Compensator. IET Power Electron, 3: 977-988.