Improving Reactive Power Compensation by Using Hybrid-STATCOM

Ramchandra Adware and V. K. Chandrakar

1 Introduction

It has long been known that it is possible to increase the steady-state power flow and control of voltage profile over a wide range by using a shunt compensating device. The reactive compensation is aimed to enhance the transmission lines' fundamental electrical parameters to make them more compliant with the prevailing demand for loads. In order to suppress line overvoltage during light load, shunt compensator with fixed and switched mechanical reactors whereas, for higher load conditions, shunt compensator with switched mechanical condensers are used. This paper is focused on some specific power quality issues to improve transmission capability by improving reactive power compensation and providing a basis for compensation and control strategies based on power electronics and obtaining specific compensation objectives. In a transmission system, the ultimate purpose of applying reactive shunt compensation is to increase the transmittable power. In order to improve the steady-state transmission characteristics as well as the reliability of the system, this may be necessary. In order to improve transient stability and the damp power system oscillations, Var compensation is, thus, used for voltage regulations, as well as for dynamic voltage control.

If we look at the Indian situation, an order of approximately EUR 78 million has been released by the Power Grid Corporation of India (PGCIL). Supply of planning and engineering facilities, as well as construction and installation of equipment in four substations at Indian Energy suppliers. In the Indian states of Bihar, Jharkhand and Odisha, Ranchi, Raurkela, Kishenganj and Jeypore substations are located:

R. Adware (✉) · V. K. Chandrakar
Department of Electrical Engineering, G. H. Raisoni College of Engineering, Nagpur, India
e-mail: ramchandra.adware@raisoni.net

V. K. Chandrakar
e-mail: vinod.chandrakar@raisoni.net

M. L. Kolhe et al. (eds.), *Smart Technologies for Energy, Environment and Sustainable Development, Vol 2*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-981-16-6879-1_59

Table 1 Characteristics of different compensators for transmission system

Compensator	Response time	Resonance problem	DC-link voltage	Compensation range	Cost
SVCs	**Slow**	Yes	–	Wide	Low
STATCOMs	Very Fast	No	**High**	Wide	**High**
C-STATCOMs	Fast	No	Low	**Narrow**	Low
PPF STATCOMs	Fast	Yes	**High**	**Narrow**	Medium
SVC/APF	Fast	Yes	**High**	Wide	**High**
Hybrid-STATCOM	Fast	No	**Low**	**Wide**	Medium

where static compensation systems can help regulate the supply of power in these regions. A subsection of Flexible AC transmission systems (FACTS) is the reactive power compensation technology. The parameters that define the function of the power supply grid and account for the transmission quality can be controlled by these systems. Transmission impedances, currents, voltages and phase angles between the various nodes are included in such parameters.

The compensation for reactive power is split into parallel compensation and serial compensation. Parallel compensation systems, such as those to be used in India, mainly control the contact point voltage and thus promote the safe and efficient operation of the grid. SVCs(Static Var Compensators) were the most traditionally used compensating device or system used, but they suffered from many problems, such as sluggish response, harmonic current injection and resonance problems [1, 2]. In order to overcome these drawbacks and improve compensation efficiency, a combined system of active power filter and a static compensator was further developed [3–8].

But those systems were very complicated and expensive. In order to resolve this, capacitor-coupled static compensator (C-STATCOM) [9] and traction power systems [10–12] have been applied to several series-based systems consisting of different forms of passive power filters. But these devices failed to have low dc-link voltages and had a very limited range of compensations (Table 1).

In order to achieve these above benefits and to boost the operational efficiency of passive power STATCOM, various control strategies have been suggested in the past to capacitive coupled STATCOM and other STATCOMS.

The instantaneous p-q principle is one of the suggested techniques. Negative control of the sequences, zero control of the sequence [7], nonlinear control [13], control method of back propagation (BP) [8], control theory based on Lypunav [14], instantaneous d-q theory, the theory of instantaneous symmetrical control [15] and the theory of hybrid voltage and current control. A hybrid combination of passive filters was also implemented in [16, 17] considering the reduction of the existing level of the active power filters and STATCOMS.

2 Circuit Configuration of Proposed System

The following circuit configuration is shown in the figure with Hybrid, traditional and Capacitor-coupled STATCOM. This device (STATCOM with TCLC filter) consists of an LC component powered by a thyristor and an active part of an inverter.

The high voltage drop between system voltage and inverter voltage can be generated by the TCLC component here from Hybrid-STATCOM. This enables the system's active inverter part to work at the voltage level at the DC bus. Due to the above reasons, the system can gain a very wide compensation for reactive power. A low-rated inverter is taken as a system part because a small rating filter enhances the output of the TCLC component by absorbing unwanted frequency signals of current produced by the TCLC. As a consequence, the mistuning of the firing angle is also avoided, which further results into the problem of voltage resonance being avoided by the system.

Figure 1 displays the hybrid-STATCOM configuration, and this is the circuit where Ls is the impedance of the transmission line and the x means the respective phase of the system, e.g. phase a, b and c.

The voltage Vsx stands for system voltage or source voltage at the respective phase and Vx means the voltage at the load with respect to phases. i_{sx}, i_{Lx} and i_{cx} are the currents of source, load and compensating current.

Hybrid-STATCOM has two parts one is a low rating inverter and another one is thyristor-controlled LC filter. First one is responsible for the tuning of the TCLC part to reduce harmonic currents whereas the second part is responsible for the reactive power compensation by tuning the firing angle of the thyristor.

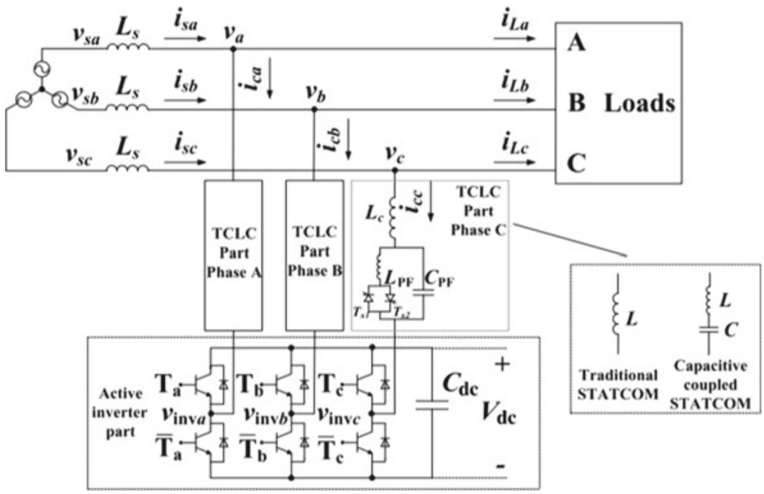

Fig. 1 3-phase system with STATCOM circuits

The low rating inverter component consists of a voltage source converter with a dc-link capacitor, and the active inverter part with a small rating is used to increase the output of the LC component operated by the thyristor.

3 V-I Characteristics

The V-I characteristics of the different types of STATCOM are observed, compared and discussed on the basis proposed system.

As shown in above Fig. 2, the inverter voltage V_{invx} is the voltage produced by the active inverter part and Vx is the reference coupling voltage. Also, loading currents show from extreme left to extreme right that inductive current is compensated from capacitive loading to inductive loading under various conditions. In conventional or traditional STATCOM, the inverter voltage required for the compensation is very high though it is providing a wide range but it requires high-rated inverter for the smooth Var compensation.

In Fig. 3 V-I characteristics of Coupled capacitor STATCOM have been drawn with respect to loading capability. Also, inverter voltage and coupling voltage are shown where it is seen that a inverter voltage is providing a wide range of magnitude of voltage from very low voltage to high but the inductive current loading capability is very narrow, which means if we go with the wide range of compensation, STATCOM may lose its control and will not able to compensate the required power.

From Fig. 4, the proposed system gives the same amount of reactive power as demanded by the load. This implies that the compensating mechanism can have the same amount of reactive power with the opposite polarity as the load. The summation

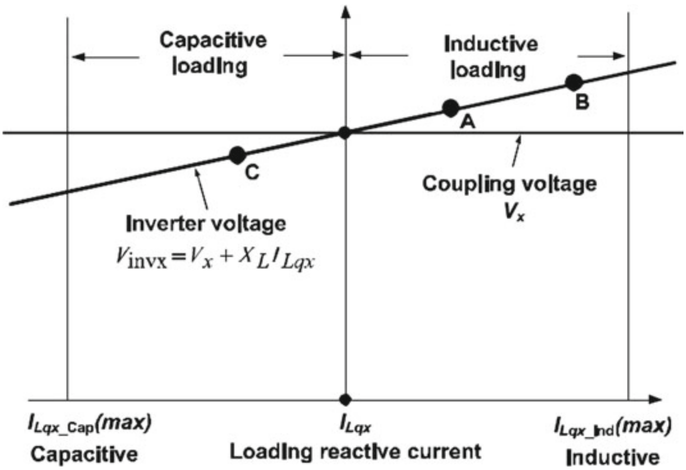

Fig. 2 Conventional STATCOM- V-I characteristics

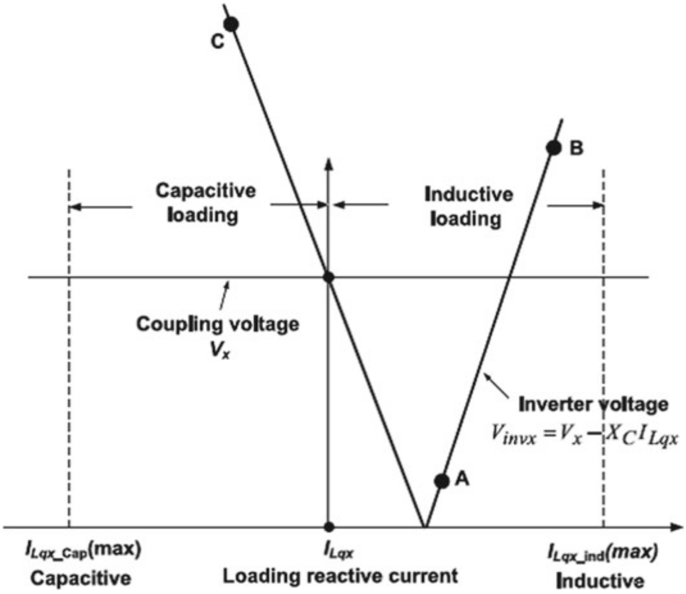

Fig. 3 C-STATCOM V-I characteristics

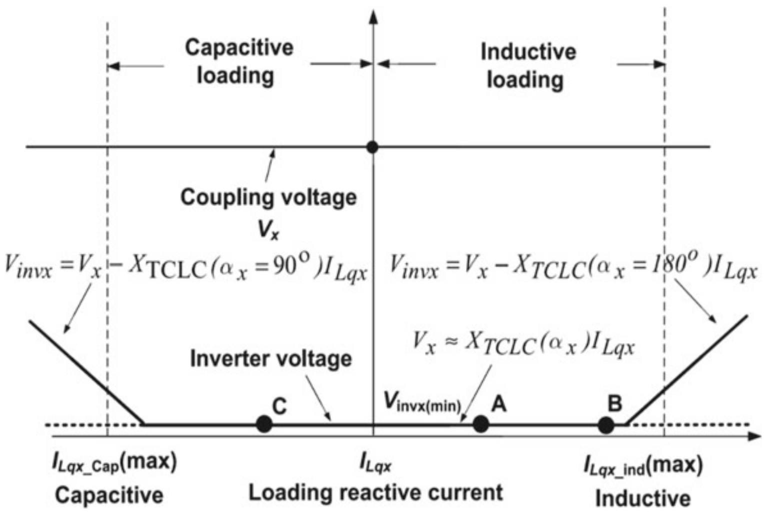

Fig. 4 Hybrid-STATCOM V-I characteristics

of the reactive power of the thyristor control LC filter part and the low-rated inverter component will, therefore, be the reactive power that will be provided.

It can be expressed as follows.

$$Q_{Lx} = -Q_{cx} = -(Q_{TCLC} + Q_{invx}) \tag{1}$$

.

In the above expression, QLx is inductive reactive power, Qcx capacitive reactive power, QTCLC is reactive power of TCLC part of the system and Qinvx is reactive power of the inverter. If the above expression (1) is expressed in voltage, then it will be as follows.

$$Q_{Lx} = V_x I_{Lqx} = -X_{TCLC}(\alpha_x) I_{cqx}^2 + V_{invx} I_{cqx} \tag{2}$$

where $X_{TCLC(\alpha x)}$ is the impedance and αx is the respective firing angle. V_x and V_{invx} are the coupling point and inverter voltages root mean squared values. I_{Lqx} and Icqx are the load RMS and reactive currents compensating value, where ILqx = -Icqx. Therefore, (2) can be simplified further as.

$$V_{invx} = V_x + X_{TCLC}(\alpha x) I_{Lqx} \tag{3}$$

.

Thus, from the above expression, the impedance of TCLC will be as follows:

$$\begin{aligned} \mathrm{X_{TCLC}}(\alpha \mathrm{x}) &= (\mathrm{X_{TCR}}(\alpha \mathrm{x})\mathrm{XCPF})/(\mathrm{XCPF} - \mathrm{XTCR}(\alpha \mathrm{x})) + \mathrm{XL_c} \\ &= [(\pi \mathrm{XLPF} \cdot \mathrm{X_{CPF}})/(\mathrm{X_{CPF}}(2\pi - 2\alpha \mathrm{x} + \sin 2\alpha \mathrm{x}) - \pi \mathrm{XLPF})] + \mathrm{XL_c} \end{aligned} \tag{4}$$

.

On the basis of the circuit and above equations, the minimum inductance and capacitance of the system can be expressed as follows:

At (αx = 90°),

$$X_{Ind\,(\min)} = \left[X_{LPF} X_{CPF} \big/ (X_{CPF} - X_{LPF})\right] + X_{Lc} \tag{5}$$

.

Similarly.

At (αx = 180°).

$$X_{Cap(\min)(\alpha x = 180\circ)} = -XCPF + XL_c \tag{6}$$

.

As shown in Fig. 4, the proposed system help to maintain minimum voltage at the inverter terminal and ensure maximum inductive and capacitive reactive current compensation.

If the reactive current required is more than the thyristor-controlled LC part, then the inverter part will increase its voltage marginally to compensate for the power. Thus, it is concluded that this proposed system can provide a wide range of compensation with low inverter voltage as shown in Fig. 4.

4 Control Scheme for the Proposed System

The control scheme for the proposed system is implemented by integrating and organizing the control of the active inverter part and the LC part of thyristor control. This is achieved with the intention that both parts of the proposed system balance each other's performance (Fig. 5).

1. TCLC filter Component: This part of the proposed system is controlled on the basis of instantaneous p-q theory and implemented to improve the system performance in terms of compensation range as well as to reduce harmonics.

$$X(TCLC) = (x)\big/(I(Lqx)) \tag{7}$$

.

   Therefore, by acquiring the necessary impedance value of TCLC, the necessary value of alpha is obtained by calculation.

2. Low rating inverter component: Its control is based on instantaneous active and reactive current id-iq model for calculating harmonic component. This part helps TCLC to improve the power compensation under various load conditions by decreasing harmonic current and continuously monitoring and compensating ref. current and measured current.

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1\big/2 & \sqrt{3}\big/2 \\ -1\big/2 & -\sqrt{3}\big/2 \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_a & -\sin\theta_a \\ \sin\theta_a & \cos\theta_a \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{8}$$

.

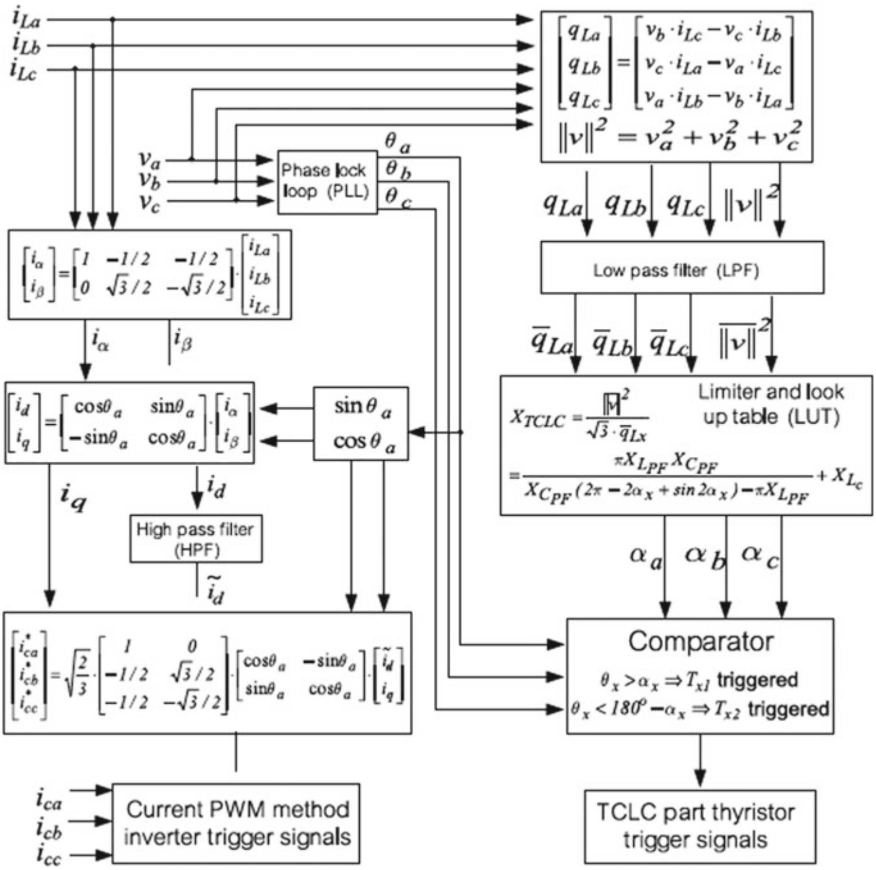

Fig. 5 Control scheme

5 Simulations and Results

In the simulation and results, four different cases are considered for the system simulation. The following table illustrates the different values considered under different situations (Table 2).

5.1 System with Light Inductive Load

In this case, system simulation is done with different types of STATCOM under light inductive load on three-phase source system and static load as shown in Fig. 1. Simulation results are obtained on MATLAB Simulink and interpreted on the basis of Var power compensation with respect to time as shown below.

Table 2 Performance parameters of STATCOM under different conditions

	Parameters	Physical values
System parameters	V_x,.*f*, *U*	110 V, 50 Hz, 0.1 rnH
Traditional STATCOM	*L*	5 mH
C-STATCOM	*L*,*C*	5 mH, 80 uF
Hybrid-STATCOM	L_c, $L_{PF,}$ C_{PF}	5 ntH, 30 ntH, 160 uF
Case *A:* inductive and light loading	L_{L1}, R_{LI}	30 mH, 14 *Q*
Case *B:* inductive and heavy loading	L_{L2}:, R_{L2}	30 mH, 9ft
Case *C:* capacitive loading	*Cu, Ru*	200 uF, 20 Q

There are three results shown in the Simulink results, and it shows reactive power. The upper graph shows load reactive power, the middle one is compensation reactive power and the lower graph shows source reactive power demand (Figs. 6, 7 and 8).

From the above graphs, it is observed that load reactive power demand is 1200 Var, and therefore, the overall compensation reactive power to be delivered by compensating device is −1300 Var and source reactive power is Var. Thus, the percentage of compensation is above 90%. Without compensating device, the source has to deliver about 90% of reactive power.

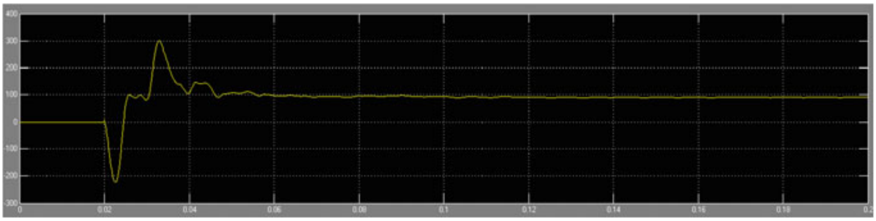

Fig. 6 Source reactive power of the lightly inductive load

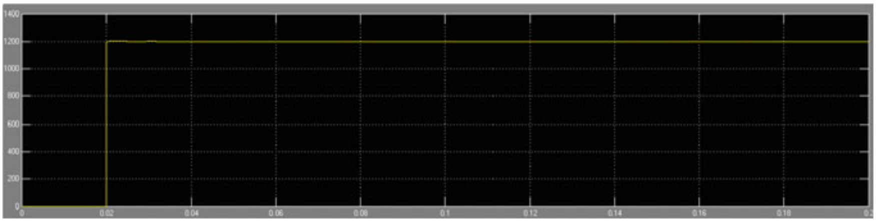

Fig. 7 Load reactive power of the lightly inductive load

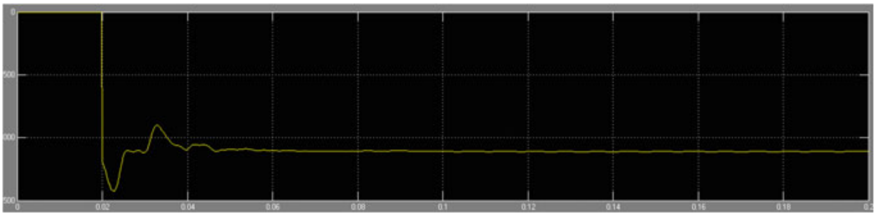

Fig. 8 Compensating reactive power of the lightly inductive load

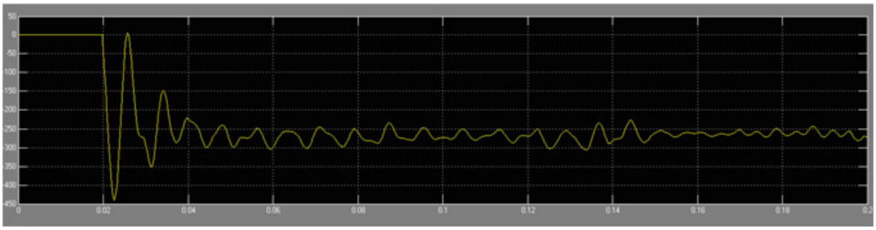

Fig. 9 Source reactive power of the heavily inductive load

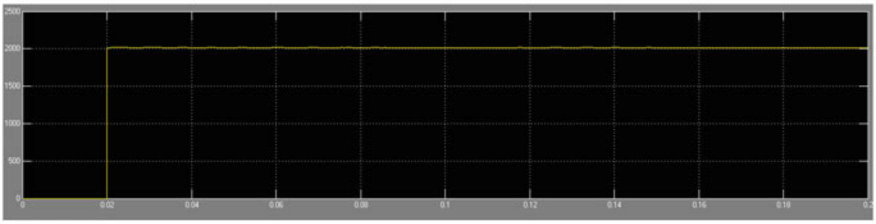

Fig. 10 Load reactive power of the heavily inductive load

5.2 System with High Inductive Load

From the following figures, a System with high inductive load shows reactive power demand of about 2000Var, compensation Var is 2250 and source reactive power 250 Var. Thus source has to bear 250 Var. Thus, the percentage of compensation is above 90% for high inductive load also (Figs. 9, 10 and 11).

5.3 System with Capacitive Load

The following figure shows the Simulink results of a system with hybrid-STATCOM with capacitive load. From the above waveforms, it is observed that load reactive power is −890, compensation reactive power is 600 and source reactive power is −290 Var. Thus, the source has to bear −290 extra. Therefore, the percentage of compensation is above 90% (Figs. 12, 13 and 14; Table 3).

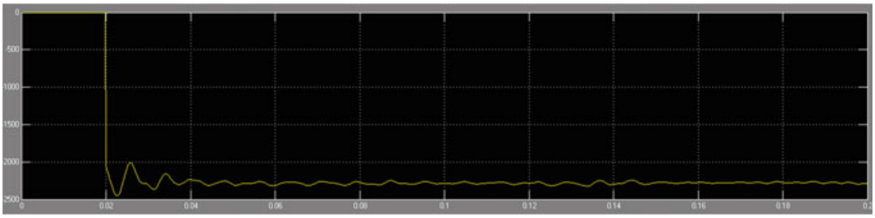

Fig. 11 Compensating reactive power of the heavily inductive load

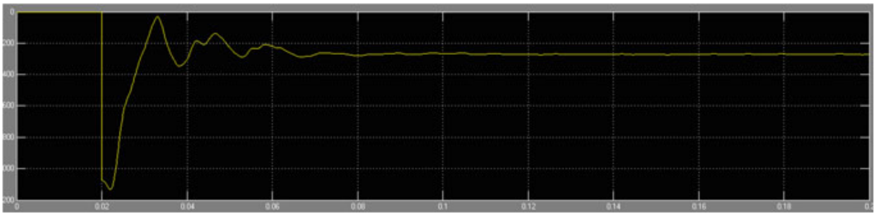

Fig. 12 Source reactive power of the capacitive load

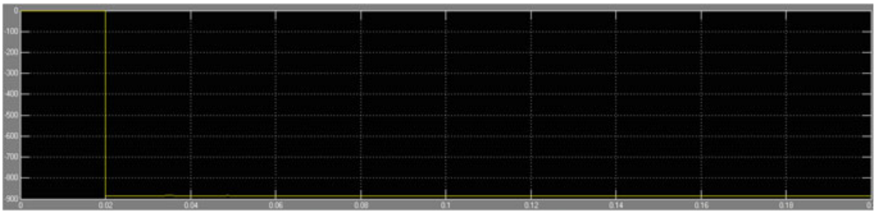

Fig. 13 Load reactive power of the capacitive load

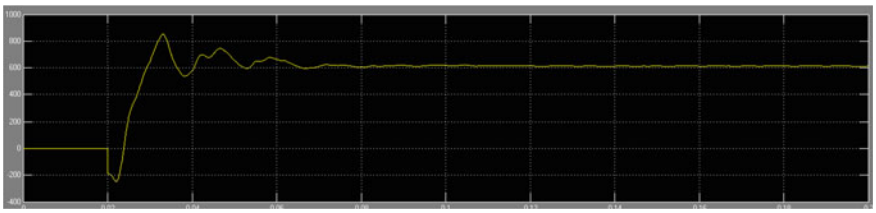

Fig. 14 Compensating reactive power of the capacitive load

Table 3 Simulation results with different types of loading conditions

Type of load	Source reactive power	Load reactive power	Compensator reactive power
Lightly inductive	100	1200	−1300
Heavily inductive	−250	2000	−2250
Capacitive	−270	−890	600

6 Conclusion

A three-phase system with different types of loads has been studied with hybrid-STATCOM and it is found to be low cost and robust in nature due to low dc bus voltage at inverter part and improved power quality and increase range in reactive power compensation with the help of TCLC filter in conjunction with the STATCOM. Performance is analysed on the basis of V-I characteristics and concluded that hybrid-STATCOM is having better performance than the traditional and coupled C-STATCOM. Control techniques are also studied and found that it is complicated than other types of STATCOM as there is a need to control both the components of the proposed system but it has been found that in terms of its performance, it is worth to do simultaneous control over the inverter and TCLC part.

References

1. J. Dixon, L. Moran, J. Rodriguez, R. Domke, Reactive power com-pensation technologies: State-of-the-art review. Proc. IEEE **93**(12), 2144–2164 (2005)
2. L. Gyugyi, R. A. Otto, T. H. Putman, Principles and applications of static thyristor-controlled shunt compensators. IEEE Trans. Power App. Syst. **PAS-97**(5), 1935–1945 (1978)
3. T. J. Dionise, Assessing the performance of a static VAR compen-sator for an electric arc furnace. IEEE Trans. Ind. Appl. **50**(3), 1619–1629 (2014)
4. F.Z. Peng, J.S. Lai, Generalized instantaneous reactive power theory for three-phase power systems. IEEE Trans. Instrum. Meas. **45**(1), 293–297 (1996)
5. L.K. Haw, M.S. Dahidah, H.A.F. Almurib, A new reactive current reference algorithm for the STATCOM system based on cas-caded multilevel inverters. IEEE Trans. Power Electron. **30**(7), 3577–3588 (2015)
6. J.A. Munoz, J.R. Espinoza, C.R. Baier, L.A. Moran, J.I. Guzman, V.M. Cardenas, Decoupled and modular harmonic compensation for multilevel STATCOMs. IEEE Trans. Ind. Electron. **61**(6), 2743–2753 (2014)
7. V. Soares, P. Verdelho, An instantaneous active and reactive cur-rent component method for active filters. IEEE Trans. Power Electron. **15**(4), 660–669 (2000)
8. M. Hagiwara, R. Maeda, H. Akagi, Negative-sequence reactive-power control by a PWM STATCOM based on a modular multilevel cascade converter (MMCC-SDBC). IEEE Trans. Ind. Appl. **48**(2), 720–729 (2012)
9. C. Kumar, M. Mishra, An improved hybrid DSATCOM topology to compensate reactive and nonlinear loads. IEEE Trans. Ind. Electron. **61**(12), 6517–6527 (2014)
10. J. He, Y.W. Li, F. Blaabjerg, Flexible microgrid power quality enhancement using adaptive hybrid voltage and current controller. IEEE Trans. Ind. Electron **61**(6), 2784–2794 (2014)

11. S. Hu, Z. Zhang, Y. Chen et al., A new integrated hybrid power quality control system for electrical railway. IEEE Trans. Ind. Electron. **62**(10), 6222–6232 (2015)
12. M.-C. Wong, C.-S. Lam, N.-Y. Dai, Capacitive-coupling STATCOM and its control. Chinese Patent 200710196710.6, May 2011
13. C.-S. Lam, M.-C. Wong, W.-H. Choi, X.-X. Cui, H.-M. Mei, J.-Z. Liu, Design and performance of an adaptive low-dc-voltage-controlled LC-Hybrid active power filter with a neutral inductor in three-phase four-wire power systems. IEEE Trans. Ind. Electron. **61**(6), 2635–2647 (2014)
14. S. Rahmani, A. Hamadi, K. Al-Haddad, A Lyapunov-function-based control for a three-phase shunt hybrid active filter. IEEE Trans. Ind. Electron. **59**(3), 1418–1429 (2012)
15. K.-W. Lao, N. Dai, W.-G. Liu, M.-C. Wong, Hybrid power quality compensator with minimum dc operation voltage design for high-speed traction power systems. IEEE Trans. Power Electron. **28**(4), 2024–2036 (2013)
16. A. Varschavsky, J. Dixon, M. Rotella, L. Moran, Cascaded nine-level inverter for hybrid-series active power filter, using industrial con-troller. IEEE Trans. Ind. Electron. **57**(8), 2761–2767 (2010)
17. L. Wang, C.-S. Lam, M.-C. Wong, A hybrid-STATCOM with wide compensation range and low DC-link voltage. IEEE Trans. Indus. Electron. **63**(6) (2016)
18. B. Singh, S.R. Arya, Back-propagation control algorithm for power quality improvement using DSTATCOM. IEEE Trans. Ind. Electron. **61**(3), 1204–1212 (2014)
19. S. Rahmani, A. Hamadi, N. Mendalek, K. Al-Haddad, A new control technique for three-phase shunt hybrid power filter. IEEE Trans. Ind. Electron. **56**(8), 2904–2915 (2009)
20. H. Akagi, K. Isozaki, A hybrid active filter for a three-phase 12-pulse diode rectifier used as the front end of a medium-voltage motor drive. IEEE Trans. Power Electron. **27**(1), 69–77 (2012)
21. S.P. Litran, P. Salmeron, Reference voltage optimization of a hybrid filter for nonlinear load reference. IEEE Trans. Ind. Electron. **61**(6), 2648–2654 (2014)
22. J. Dixon, Y. del Valle, M. Orchard, M. Ortuzar, L. Moran, C. Maffrand, A full compensating system for general loads, based on a combination of thyristor binary compensator, and a PWM-IGBT active power filter. IEEE Trans. Ind. Electron. **50**(5), 982–989 (2003)
23. W. Y. Dong, Research on control of comprehensive compensation for traction substations based on the STATCOM technology. Ph.D. dissertation, Tsinghua University, Beijing, China (2009)