Design of Hybrid-STATCOM with TCLC with High Compensation Range and for Low DC-Link Voltage

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***Abstract*: This paper proposes a hybrid static synchronous compensator (hybrid-STATCOM) in a three-phase power transmission system that has a wide remuneration range and low DC-link voltage. As a result of these conspicuous attributes, the system expenses can be enormously decreased. In this paper, the circuit configuration of hybrid-STATCOM is presented first. Its V-I trademark is then dissected, talked about, and contrasted and customary STATCOM and capacitive-coupled STATCOM (C-STATCOM). The system parameter configuration is then proposed on the premise of consideration of the reactive power pay range and shirking of the potential reverberation issue. From that point forward, a control system for hybrid-STATCOM is proposed to permit operation under various voltage and current conditions, for example, uneven current, voltage plunge, and voltage fault. At long last, simulation and trial results are given to check the wide remuneration range and low DC-link voltage attributes and the great dynamic execution of the proposed hybrid-STATCOM.**

***Index Terms*—Capacitive-coupled static synchronous compensator (C-STATCOM), hybrid static synchronous compensator (hybrid STATCOM), static synchronous compensator (STATCOM), wide compensation range, low DC-link voltage.**

I. INTRODUCTION

THE expansive reactive current in transmission systems is a standout amongst the most widely recognized power issues that builds transmission losses and brings down the dependability of a power system [1]-[19]. Utilization of reactive power compensators is one of the answers for this issue. Static VAR compensators (SVCs) are customarily used to dynamically remunerate reactive currents as the loads differ occasionally. Notwithstanding, SVCs experience the ill effects of numerous issues, for example, reverberation issues, harmonic current infusion, and moderate reaction [2]-[3]. To defeat these impediments, static synchronous compensators (STATCOMs) and active power filters (APFs) were produced for reactive current pay with speedier reaction, less harmonic current infusion, and better execution [4]-[9]. In any case, the STATCOMs or APFs as a rule require multilevel structures in a medium-or high-voltage level transmission system to decrease the high-voltage worry over each power switch and DC-link capacitor, which drives up the underlying and operational expenses of the system and furthermore builds the control intricacy.

Afterward, series-sort capacitive-coupled STATCOMs (C-STATCOMs) were proposed to decrease the system DC-link working voltage necessity [10], and different series-sort hybrid structures that comprise of various passive power filters (PPFs) in series with STATCOMs or APF structures (PPF-STATCOMs) have been connected to power distribution systems [11]-[16] and footing power systems [17]-[19]. Be that as it may, C-STATCOMs and different series-sort PPF-STATCOMs contain generally limit reactive power pay ranges. At the point when the required repaying reactive power is outside their remuneration extends, their system exhibitions can fundamentally decay.

To enhance the working exhibitions of the conventional STATCOMs, C-STATCOMs, and other PPF-STATCOMs, a wide range of control procedures have been proposed, for example, the instantaneous p-q theory [4], [10], [11], [17] [19], the instantaneous d-q theory [5], [6], [14], the instantaneous id-iq strategy [7], negative-and zero-sequence control [8], the back spread (BP) control technique [9], nonlinear control [12], Lyapunov-function-based control [13], instantaneous symmetrical component theory [15], and hybrid voltage and current control [16].

To diminish the present rating of the STATCOMs or APFs, a hybrid combination structure of PPF in parallel with STATCOM (PPF//STATCOM) was proposed in [20] and [21]. Nonetheless, this hybrid compensator is devoted for inductive loading operation. When it is connected for capacitive loading pay, it effectively loses its little active inverter rating qualities. To expand the remuneration range and keep low current rating normal for the APF, Dixon et al. [22] proposed another hybrid combination structure of SVC in parallel with APF (SVC//APF) in three-phase distribution systems.

In this hybrid structure, the APF is controlled to take out the harmonics and make up for the little measures of load reactive and uneven power left by the SVC. Be that as it may, if this structure is connected in a medium-or high-voltage level transmission system, the APF still requires an exorbitant voltage step-down transformer as well as multilevel structure. What's more, these two parallel associated hybrid STATCOM structures [15]-[17] may experience the ill effects of a reverberation issue. To beat the deficiencies of various reactive power compensators [1]-[22] for transmission systems, this paper proposes a hybrid-STATCOM that comprises of a thyristor-controlled LC part (TCLC) and an active inverter part, as appeared in Fig. 1.

The TCLC part gives a wide reactive power remuneration go and an expansive voltage drop between the system voltage and the inverter voltage with the goal that the active inverter part can keep on operating at a low DC-link voltage level. The little evaluating of the active inverter part is utilized to enhance the exhibitions of the TCLC part by retaining the harmonic currents created by the TCLC part, abstaining from mistuning of the terminating edges, and keeping the reverberation issue. The commitments of this paper are abridged as takes after:

1) A hybrid-STATCOM is proposed, with the unmistakable attributes of a considerably more extensive pay go than C-STATCOM [10] and different series-sort PPF-STATCOMs [11]-[19] and a much lower DC-link voltage than customary STATCOM [4]-[9] and other parallel-associated hybrid STATCOMs [20]-[22].

2) Its V-I trademark is broke down to give an unmistakable perspective of the upsides of hybrid-STATCOM in correlation with conventional STATCOM and C-STATCOM.

3) Its parameter outline technique is proposed based on consideration of the reactive power remuneration extend, aversion of the potential reverberation issue and shirking of mistuning of terminating point.

4) Another control technique for hybrid-STATCOM is proposed to facilitate the TCLC part and the active inverter part for reactive power remuneration under various voltage and current conditions, for example, unequal current, voltage fault, and voltage plunge.

The attributes of various reactive power compensators and the proposed hybrid-STATCOM for the transmission system are looked at and outlined in Table I.

TABLE I
CHARACTERISTICS OF DIFFERENT COMPENSATORS FOR TRANSMISSION SYSTEM

	Response time	Resonance problem	DC-link voltage	Compensation range	Cost
SVCs [2]-[3]	Slow	Yes	--	Wide	Low
STATCOMs [4]-[9]	Very Fast	No	High	Wide	High
C-STATCOMs [10]	Fast	No	Low	Narrow	Low
Series-type PPF-STATCOMs [11]-[19]	Fast	No	Low	Narrow	Low
PPF//STATCOM [20], [21]	Fast	Yes	High	Narrow	Medium
SVC//APF [22]	Fast	Yes	High	Wide	High
Hybrid-STATCOM	Fast	No	Low	Wide	Medium

**Shaded areas indicate an unfavorable characteristic.*

In this paper, the system configuration of the proposed hybrid-STATCOM is introduced in section II. In section III, the V-I characteristic of hybrid STATCOM is proposed in comparison with traditional STATCOM and C-STATCOM. The parameter design and control strategy of the hybrid-STATCOM are then proposed in Sections IV and V. Finally, the simulation (Section VI) and experimental results (Section VII) are provided to prove the wide compensation range and low DC-link voltage characteristics and the dynamic performance of the proposed hybrid-STATCOM.

II. CIRCUIT CONFIGURATION OF THE HYBRID-STATCOM

Fig. 1 demonstrates the circuit configuration of hybrid-STATCOM, in which the subscript "x" remains for phase a, b, and c in the accompanying investigation. vsx and vx are the source and load voltages; isx, iLx, and icx are the source, load, and remunerating currents, individually. Ls is the transmission line impedance. The hybrid-STATCOM comprises of a TCLC and an active inverter part.

The TCLC part is made out of a coupling inductor Lc, a parallel capacitor CPF, and a thyristors-controlled reactor with LPF. The TCLC part gives a wide and ceaseless inductive and capacitive reactive power pay go that is controlled by controlling the terminating edges □x of the thyristors. The active inverter part is made out of a voltage source inverter with a DC-link capacitor Cdc, and the little evaluating active inverter part is utilized to enhance the execution of the TCLC part. Moreover, the coupling components of the customary STATCOM and C-STATCOM are additionally exhibited in Fig. 1.Based on the circuit configuration in Fig. 1, the V-I qualities of conventional STATCOM, C-STATCOM, and hybrid-STATCOM are thought about and examined.

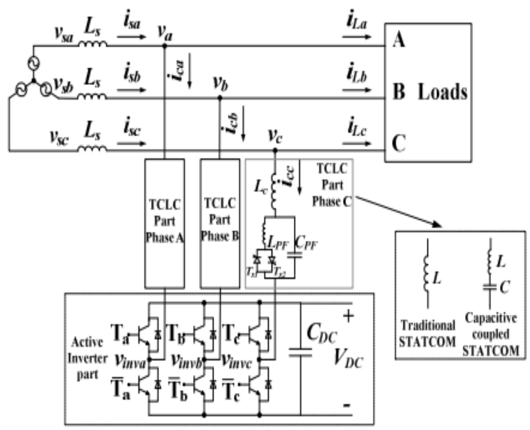


Fig. 1. Circuit configuration of the hybrid-STATCOM.

III. V-I CHARACTERISTICS OF THE TRADITIONAL STATCOM, C-STATCOM AND HYBRID-STATCOM

The purpose of the hybrid-STATCOM is to provide the same amount of reactive power as the loadings (*QLx*) consumed, but with the opposite polarity (*Qcx*=*-QLx*). The hybrid-STATCOM compensating reactive power *Qcx* is the sum of the reactive power *QTCLC* that is provided by the TCLC part and the reactive power *Qinvx* that is provided by the active inverter part. Therefore, the relationship among *QLx*, *QTCLC*, and *Qinvx* can be expressed as

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

The reactive powers can also be expressed in terms of voltages and currents as

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

where *XTCLC(〈x)* is the coupling impedance of the TCLC part; 〈*x* is the corresponding firing angle; *Vx* and *Vinvx* are the root mean square (RMS) values of the coupling point and the inverter voltages; and *ILqx* and *Icqx* are the RMS value of the load and compensating reactive currents, where *ILqx*=*-Icqx*. Therefore, (2) can be further simplified as

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

where the TCLC part impedance *XTCLC(〈x)* can be expressed as

$$X_{TCLC}(\alpha_x) = \frac{X_{TCR}(\alpha_x) X_{C_{PF}}}{X_{C_{PF}} - X_{TCR}(\alpha_x)} + X_{L_c} = \frac{\pi X_{L_{PF}} X_{C_{PF}}}{X_{C_{PF}}(2\pi - 2\alpha_x + \sin 2\alpha_x) - \pi X_{L_{PF}}} + X_{L_c} \tag{4}$$

Where *X Lc* , *XLPF* , and *XCPF* are the fundamental impedances of *Lc*, *LPF*, and *CPF*, respectively. In (4), it is shown that the TCLC part impedance is controlled by firing angle α*x*. And the minimum inductive and capacitive impedances (absolute value) of the TCLC part can be obtained by substituting the firing angles α*x=90o* and α*x=180o*, respectively. In the following discussion, the minimum value for impedances stands for its absolute value. The minimum inductive (*Xind(min)*>0) and capacitive (*XCap(min)*<0) TCLC part impedances can be expressed as

$$X_{Ind(min)}(\alpha_x = 90^\circ) = \frac{X_{L_{PF}} X_{C_{PF}}}{X_{C_{PF}} - X_{L_{PF}}} + X_{L_c} \tag{5}$$

$$X_{Cap(min)}(\alpha_x = 180^\circ) = -X_{C_{PF}} + X_{L_c} \tag{6}$$

Ideally, *XTCLC(*α*x)* is controlled to be *Vx =(XTCLC(αx)ILqx* , so that the minimum inverter voltage (*V invx~~0*) can be obtained as shown in (3). In this case, the switching loss and switching noise can be significantly reduced. A small inverter voltage *Vinvx(min)* is necessary to absorb the harmonic current generated by the TCLC part, to prevent a resonance problem, and to avoid mistuning the firing angles. If the loading capacitive current or inductive current is outside the TCLC part compensating range, the inverter voltage *Vinvx* will be slightly increased to further enlarge the compensation range.

The coupling impedances for traditional STATCOM and C-STATCOM, as shown in Fig. 1, are fixed as *XL* and *XC-1/XL*. The relationships among the load voltage *Vx*, the inverter voltage *Vinvx*, the load reactive current *ILqx*, and the coupling impedance of traditional STATCOM and C-STATCOM can be expressed as

$$V_{invx} = V_x + X_L I_{Lqx} \tag{7}$$

$$V_{invx} = V_x - \left(X_C - \frac{1}{X_L}\right) I_{Lqx} \tag{8}$$

where *XL* >> *XC*. Based on (3)-(8), the V-I characteristics of the traditional STATCOM, C-STATCOM, and hybrid-STATCOM can be plotted as shown in Fig. 2.

For conventional STATCOM as appeared in Fig. 2(a), the required Vinvx is bigger than Vx when the loading is inductive. Conversely, the required Vinvx is littler than Vx when the loading is capacitive. As a matter of fact, the required inverter voltage Vinvx is near the coupling voltage Vx, because of the little benefit of coupling inductor L [5]-[8].

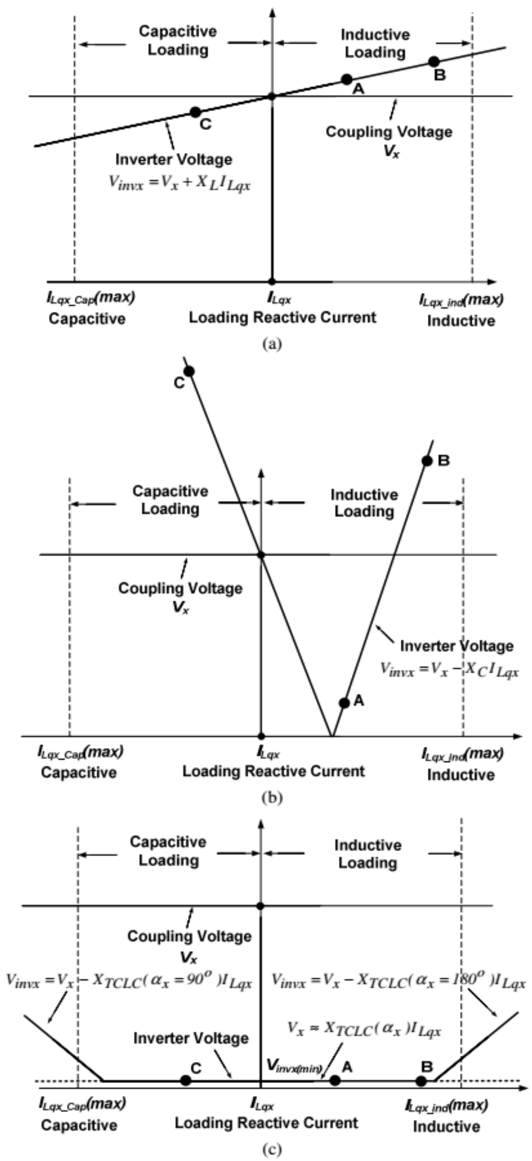


Fig2. V-I characteristic of (a) traditional STATCOM, (b) C-STATCOM, and (c) hybrid-STATCOM.

For C-STATCOM as appeared in Fig. 2(b), it is demonstrated that the required Vinvx is lower than Vx under a little inductive loading range. The required Vinvx can be as low as zero when the coupling capacitor can fully make up for the loading reactive current. Conversely, Vinvx is bigger than Vx when the loading is capacitive or outside its little inductive loading range. Consequently, when the loading reactive current is outside its outlined inductive range, the required Vinvx can be substantial.

For the proposed hybrid-STATCOM as appeared in Fig. 2(c), the required Vinvx can be maintained at a low (least) level (Vinvx(min)) for a huge inductive and capacitive reactive current range. Also, when the loading reactive current is outside the pay scope of the TCLC part, the Vinvx will be somewhat expanded to additionally augment the repaying range. Contrasted and customary STATCOM and C-STATCOM, the proposed hybrid-STATCOM has a predominant V-I normal for a vast remuneration extend with low inverter voltage.

Furthermore, three cases spoke to by points A, B, and C in Fig. 2 are mimicked in Section VI. Based on Fig. 1, the parameter outline of hybrid-STATCOM is examined in the accompanying segment.

IV. PARAMETER DESIGN OF HYBRID-STATCOM

The proposed TCLC part is a recently proposed SVC structure which planned based on the premise of the consideration of the reactive power remuneration extend (for LPF and CPF) and the aversion of the potential reverberation issue (for Lc). The active inverter part (DC-link voltage VDC) is intended to abstain from mistuning of the terminating point of TCLC part.

A. Design of CPF and LPF

The motivation behind the TCLC part is to give a similar measure of remunerating reactive power Qcx, TCLC(x) as the reactive power required by the loads QLx yet with the other way. In this manner, CPF and LPF are composed on the premise of the maximum capacitive and inductive reactive power. The repaying reactive power Qcx go in term of TCLC impedance XTCLC(x) can be communicated as

$$Q_{cx,TCLC}(\alpha_x) = \frac{V_x^2}{X_{TCLC}(\alpha_x)} \tag{9}$$

Where *Vx* is the RMS value of the load voltage and *XTCLC(αx)* is the impedance of the TCLC part, which can be obtained from (4). In (9), when the *XTCLC(αx)=XCap(min)(αx=180°)*

And

XTCLC(αx)=XInd(min)(αx=90°), the TCLC part provides the maximum capacitive and inductive compensating reactive power *Qcx(MaxCap)* and *Qcx(MaxInd)*, respectively.

$$Q_{cx(MaxCap)} = \frac{V_x^2}{X_{Cap(min)}(\alpha_x = 180°)} = -\frac{V_x^2}{X_{C_{PF}} - X_{L_c}} \quad (10)$$

$$Q_{cx(MaxInd)} = \frac{V_x^2}{X_{Ind(min)}(\alpha_x = 90°)} = \frac{V_x^2}{\frac{X_{L_{PF}} X_{C_{PF}}}{X_{C_{PF}} - X_{L_{PF}}} + X_{L_c}} \quad (11)$$

where the minimum inductive impendence *XInd(min)* and the capacitive impendence *XCap(min)* are obtained from (5) and (6), respectively.

To compensate for the load reactive power (*Qcx* =- *QLx*), *CPF* and *LPF* can be deduced on the basis of the loading maximum inductive reactive power *QLx(MaxInd)* (=-*Qcx(MaxCap)*) and capacitive reactive power *QLx(MaxCap)* (=-*Qcx(MaxInd)*). Therefore, based on (10) and (11), the parallel capacitor *CPF* and inductor *LPF* can be designed as

$$C_{PF} = \frac{Q_{Lx(MaxInd)}}{\omega^2 Q_{Lx(MaxInd)} L_c + \omega V_x^2} \quad (12)$$

$$L_{PF} = \frac{V_x^2 + \omega L_c Q_{Lx(MaxCap)}}{-\omega Q_{Lx(MaxCap)} + \omega^3 L_c C_{PF} Q_{Lx(MaxCap)} + \omega^2 V_x^2 C_{PF}} \quad (13)$$

where ω is the fundamental angular frequency and *Vx* is the RMS load voltage.

B. Design of Lc

For energizing reverberation issues, an adequate level of harmonic source voltages or currents must be available at or close to the thunderous frequency. In this way, Lc can be intended to tune the reverberation points to separate from the overwhelmed harmonic requests nd=6n +1th (n=1, 2, 3…) of a three-phase three-wire transmission system to stay away from the reverberation issue.

The thyristors (Tx1 and Tx2) for each phase of the TCLC part can be considered as a couple of bidirectional switches that create low-arrange harmonic currents when the switches change states. The improved single-phase proportionate circuit model of hybrid-STATCOM is appeared in Fig. 3.

Alluding to Fig. 3, when turn S is killed, the TCLC part can be considered as the Lc in series with CPF, which is called LC-mode. Interestingly, when switch S is turned on, the TCLC can be considered as the L c in series with the combination of CPF in parallel with LPF, which is called LCL-mode.

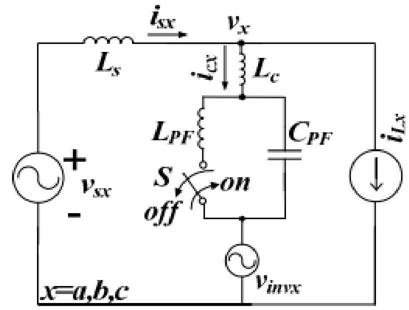


Fig3. Simplified single-phase equivalent circuit model of hybrid-STATCOM

From Table IV in the *Appendix A*, the TCLC part harmonic impedances under *LC*-mode and *LCL* mode at different harmonic order *n* can be plotted in Fig. 4 and are expressed as following

$$X_{LC,n}(n) = \left| \frac{1-(n\omega)^2 L_C C_{PF}}{n\omega C_{PF}} \right| \quad (14)$$

$$X_{LCL,n}(n) = \left| \frac{n\omega(L_c + L_{PF}) - (n\omega)^3 L_{PF} L_c C_{PF}}{1-(n\omega)^2 L_{PF} C_{PF}} \right| \quad (15)$$

In (14) and (15), there are two series resonance points *n1* at *XLC,n*(*n1*)=0 and *n2* at *XLCL,n*(*n2*)=0 and a parallel resonance point *n3* at *XLCL,n*(*n3*)= +∞. *Lc* can be designed to tune the resonance points *n1* and *n2* to diverge from the dominated harmonic orders *nd=6n±1th* (*n=1, 2, 3…*) or approach the *3n th* order in a three-phase three-wire system. Based on the above discussion, the design criteria of *Lc* can be expressed as

$$L_c = \frac{1}{(\omega n_1)^2 C_{PF}} \text{ and } L_c = \frac{1}{(\omega n_2)^2 C_{PF} - 1/L_{PF}} \quad (16)$$

$$n_3 = \frac{1}{\sqrt{L_{PF} C_{PF} \omega^2}} \quad (n_1, n_2 \text{ and } n_3 \text{ away from } n_d) \quad (17)$$

In (16), they can be satisfied simultaneously as long as *n1* and *n2* are away from the dominated harmonic orders *nd*. The designed *CPF* and *LPF* should also satisfy (17). In this paper, *n1* = 3.6, *n2* =3.9, and *n3*=1.5 are chosen.

C. Design of VDC

Different with the traditional *VDC* design method of the STATCOM to compensate maximum load reactive power, the *VDC* of Hybrid-STATCOM is design to solve the firing angle mistuning problem of TCLC (i.e., affect the reactive power compensation) so that the source reactive power can be fully compensated.

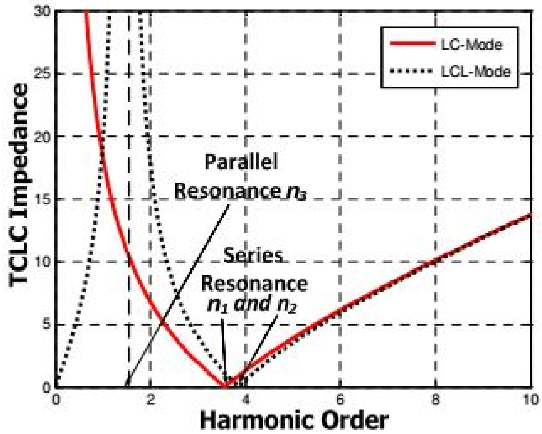


Fig4. TCLC impedance under different harmonic order.

Reforming (3), the inverter voltage *Vinvx* can also be expressed as

$$V_{invx} = V_x\left[1+\frac{V_x I_{Lqx}}{V_x^2 / X_{TCLC}(\alpha_x)}\right] = V_x\left[1+\frac{Q_{Lx}}{Q_{cx,TCLC}(\alpha_x)}\right] \quad (18)$$

where *QLx* is the load reactive power, *Qcx,TCLC*(αx) is the TCLC part compensating reactive power, and *Vx* is the RMS value of the load voltage. Combing (18) with $V_{DC} = \sqrt{6}\left|V_{invx}\right|$, the required DC-link voltage *VDC* for hybrid-STATCOM can be expressed as

$$V_{DC} = \sqrt{6}V_x\left|1+\frac{Q_{Lx}}{Q_{cx,TCLC}(\alpha_x)}\right| \quad (19)$$

Ideally, *Qcx,TCLC*(αx) is controlled to be equal to –*QLx* so that the required *VDC* can be zero. However, in the practical case, the *Qcx,TCLC*(αx) may not be exactly equal to –*QLx* due to the firing angle mistuning problem. The worst case of mistuning *QLx*/*Qcx,TCLC*(αx) ratio can be pre-measured to estimate the required minimum *VDC* value. Finally, a slightly greater *VDC* value can be chosen.

Based on (12), (13), (16), and (19), the system parameters *CPF, LPF, Lc,* and *VDC* of hybrid-STATCOM can be designed accordingly. In the following section, the control strategy of hybrid-STATCOM is proposed and discussed.

V. CONTROL STRATEGY OF HYBRID-STATCOM

In this segment, a control technique for hybrid-STATCOM is proposed by organizing the control of the TCLC part and the active inverter part with the goal that the two sections can supplement each other's weaknesses and the general execution of hybrid-STATCOM can be improved. In particular, with the proposed controller, the reaction time of hybrid-STATCOM can be speedier than SVCs, and the active inverter part can work at bring down dc-link working voltage than the customary STATCOMs. The control procedure of hybrid-STATCOM is isolated into two sections for talk: A. TCLC part control and B. Active inverter part control. The reaction time of hybrid-STATCOM is talked about to a limited extent C. The control block diagram of hybrid-STATCOM is appeared in Fig. 5.

A. TCLC part control

Diverse with the conventional SVC control based on the customary meaning of reactive power [2]-[3], to enhance its reaction time, the TCLC part control is based on the instantaneous pq theory [4]. The TCLC part is mainly used to remunerate the reactive current with the controllable TCLC part impedance XTCLC. Alluding to (3), to get the base inverter voltage Vinvx□0 , XTCLC can be ascertained with Ohm's law as far as the RMS estimations of the load voltage (Vx) and the load reactive current (ILqx). In any case, to compute the XTCLC progressively, the outflow of XTCLC can be revised regarding instantaneous esteems as

$$X_{TCLC} = \frac{V_x}{I_{Lqx}} = \frac{\overline{\|v\|}^2}{\sqrt{3}\cdot \bar{q}_{Lx}} \quad (20)$$

where ‖*v*‖ is the norm of the three-phase instantaneous load voltage and *qLx* is the DC component of the phase reactive power. The real-time expression of ‖*v*‖ and *qLx* can be obtained by (21) and (22) with low-pass filters.

$$\|v\| = \sqrt{v_a^2 + v_b^2 + v_c^2} \quad (21)$$

$$\begin{bmatrix} q_{La} \\ q_{Lb} \\ q_{Lc} \end{bmatrix} = \begin{bmatrix} v_b \cdot i_{Lc} - v_c \cdot i_{Lb} \\ v_c \cdot i_{La} - v_a \cdot i_{Lc} \\ v_a \cdot i_{Lb} - v_b \cdot i_{La} \end{bmatrix} \quad (22)$$

In (21) and (22), vx and qLx are the instantaneous load voltage and the load reactive power, separately. As appeared in Fig. 5, a limiter is connected to constrain the computed XTCLC in (9) inside the scope of XTCLC>Xind(min) and XTCLC<XCap(min) (XCap(min)<0). With the ascertained XTCLC, the terminating edge αx can be dictated by tackling (4). Since (4) is convoluted, a look-into table (LUT) is introduced inside the controller.

The trigger signals to control the TCLC part would then be able to be produced by contrasting the terminating edge αx and θx, which is the phase point of the load voltage vx. θx can be gotten by utilizing a phase bolt circle (PLL). Note that the terminating edge of each phase can contrast if the uneven loads are associated (see (4) and (20)). With the proposed control calculation, the reactive power of each phase can be repaid and the active power can be essentially adjusted, so DC link voltage can be maintained at a low level even under unequal load pay.

B. Active inverter part control

In the proposed control technique, the instantaneous active and reactive current id-iq strategy [7] is executed for the active inverter part to enhance the general execution of hybrid-STATCOM under various voltage and current conditions, for example, adjusted/unequal, voltage plunge, and voltage fault. In particular, the active inverter part is utilized to enhance the TCLC part trademark by restricting the remunerating current icx to its reference esteem icx* with the goal that the mistuning issue, the reverberation issue, and the harmonic infusion issue can be stayed away from. The icx* is ascertained by applying the id-iq strategy [7] on the grounds that it is legitimate for various voltage and current conditions.

The figured icx* contains reactive power, unequal power, and current harmonic components. By controlling the repaying current icx to track its reference icx*, the active inverter part can make up for the load harmonic currents and enhance the reactive power pay capacity and dynamic execution of the TCLC part under various voltage conditions. The icx* can be ascertained as following

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_a & -\sin\theta_a \\ \sin\theta_a & \cos\theta_a \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_d \\ i_q \end{bmatrix} \quad (23)$$

where *id* and *iq* are the instantaneous active and reactive current, which include DC components *id* and *iq* , and AC components $\tilde{i_d}$ and $\tilde{i_q}$. *id* is obtained by passing *id* through a high-pass filter. *id* and *iq* are obtained by

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta_a & \sin\theta_a \\ -\sin\theta_a & \cos\theta_a \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (24)$$

In (24), the currents (*i*α and *i*β) in α-β plane are transformed from *a-b-c* frames by

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (25)$$

Where *iLx* is the load current signal.

C. Response time of hybrid-STATCOM

The TCLC part has two consecutive associated thyristors in each phase that are activated on the other hand in each half cycle, with the goal that the control period of the TCLC part is one cycle (0.02 s). In any case, the proposed hybrid-STATCOM structure interfaces the TCLC part in series with an instantaneous worked active inverter part, which can altogether enhance its general reaction time.

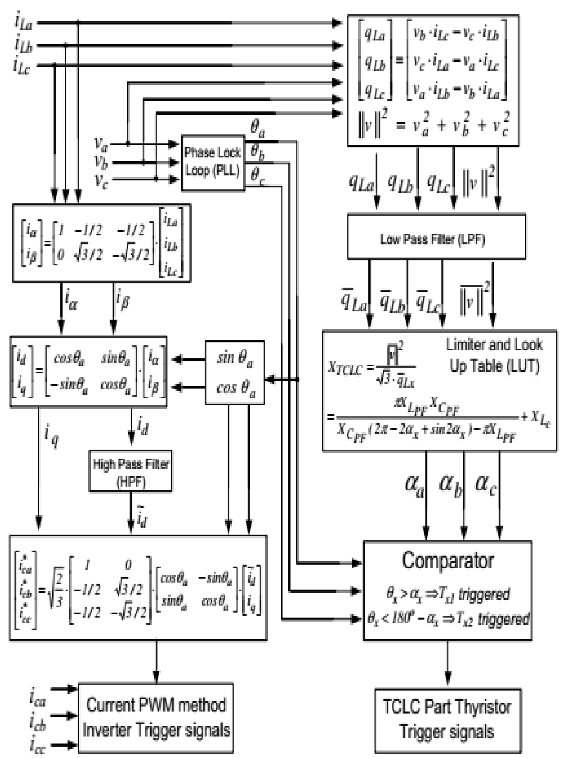


Fig5. The control block diagram of hybrid-STATCOM.

With the proposed controller, the active inverter part can restrain the remunerating current icx to its reference esteem icx* by means of pulse width adjustment (PWM) control, and the PWM control frequency is set to be 12.5 kHz. Amid the transient state, the reaction time of hybrid-STATCOM can be independently examined in the accompanying two cases. an) If the load reactive power is dynamically changing inside the inductive range (or inside the capacitive range), the reaction time of hybrid-STATCOM can be as quick as customary STATCOM. b) conversely, when the load reactive power abruptly changes from capacitive to inductive or the other way around, the hybrid-STATCOM may take roughly one cycle to settle down. Be that as it may, in functional application, case b) portrayed above at times happens. Along these lines, based on the above dialog, the proposed hybrid STATCOM can be considered as a quick reaction reactive power compensator in which the dynamic exhibitions of hybrid-STATCOM are demonstrated by the simulation result (Fig. 6) and the trial results (Fig. 7, Fig. 8, Fig. 10, and Fig. 12).

The accompanying segment reports the simulation and trial results to confirm the above V-I attributes investigation and the control procedure of the hybrid-STATCOM in examination with customary STATCOM and C-STATCOM.

VI. SIMULATION RESULTS

In this area, the simulation results among customary STATCOM, C-STATCOM, and the proposed hybrid-STATCOM are examined and analyzed. The past discourses of the required inverter voltages (or DC-link voltage Vdc=32V) for these three STATCOMs are likewise checked by simulations. The STATCOMs are mimicked with a similar voltage level as in the trial results in Section VI.

The simulation examines are completed with PSCAD/EMTDC. Table IV in the Appendix A demonstrates the simulation system parameters for conventional STATCOM, C-STATCOM, and hybrid STATCOM. Likewise, three unique instances of loading are worked for testing: A. inductive and light loading, B. inductive and overwhelming loading, and C. capacitive loading. These three testing cases are likewise spoken to by points A, B, and C in Fig. 2. The nitty gritty simulation results are compressed in Table II. At long last, the dynamic reaction of hybrid-STATCOM is reenacted and talked about in this area part D. With the consideration of IEEE standard 519 2014 [24], total request distortion (TDD) =15% and ISC/IL in 100<1000 scale at a run of the mill case, the ostensible rate current is thought to be equivalent to the fundamental load current in the most pessimistic scenario investigation, which results in THD=TDD=15%. Hence, this paper assesses the remuneration execution by setting THD<15%.

A. Inductive and light loading

At the point when the loading is inductive and light, conventional STATCOM requires a high DC-link voltage (Vdc>□2VL−L=269V, Vdc=300V) for remuneration. After pay, the source current isx is lessened to 5.55A from 6.50A and the source-side dislodging power factor (DPF) progresses toward becoming solidarity from 0.83. Likewise, the source current total harmonics distortion (THDisx) is 7.22% after pay, which fulfills the international standard [24] (THDisx<15%).

For C-STATCOM, the coupling impedance contributes a huge voltage drop between the load voltage and the inverter voltage with the goal that the required DC-link voltage can be little (Vdc=80V). The isx, DPF and THDisx are remunerated to 5.48A, solidarity, and 2.01%, individually.

For the proposed hybrid-STATCOM, the isx, DPF, and THDisx are repaid to 5.48A, solidarity, and 1.98%, individually. As talked about in the past segment, a low DC-link voltage (Vdc=50V) of hybrid STATCOM is utilized to abstain from mistuning of terminating edges, avoid reverberation issues, and decrease the infused harmonic currents.

B. Inductive and heavy loading

To make up for the inductive and substantial loading, conventional STATCOM still requires a high DC-link voltage of Vdc=300V for remuneration. Conventional STATCOM can acquire worthy results (DPF = 1.00 and THDisx = 6.55%). The isx is decreased to 5.95A from 8.40A after pay.

With a low DC-link voltage (Vdc=50V), C-STATCOM can't give satisfactory remuneration results (DPF = 0.85 and THDisx =17.5%). Be that as it may, when the DC-link voltage is expanded to Vdc=300V, the remuneration results (DPF = 1.00 and THDisx= 7.02%) are adequate and fulfill the international standard [24] (THDisx<15%). The isx is decreased to 5.90A from 8.40A after pay.

Then again, the proposed hybrid-STATCOM can at present get adequate pay results (DPF = 1.00 and THDisx = 3.01%) with a low DC-link voltage of Vdc=50V. The isx is diminished to 5.89A from 8.40A after pay.

C. Capacitive loading

When the loading is capacitive, with Vdc=250V ($Vdc<\sqrt{2}VL-L=269V$), the compensation results of traditional STATCOM are acceptable, in which the *DPF* and *THDisx* are compensated to unity and 7.61%. The *isx* is also reduced to 3.67A from 4.34A after compensation.

For C-STATCOM with *Vdc*= 50V, the *isx* increases to 7.10A from the original 4.34A. The compensation performances (*DPF*=0.57 and *THDisx*=23.5%) are not satisfactory, which cannot satisfy the international standard [24] (*THDisx*<15%). When *Vdc* is increased to 500V, the *DPF* is improved to 0.99 and the *THDisx* is reduced to 10.6%, which can be explained by its V-I characteristic. However, the compensated *isx*=5.02A is still larger than *isx*=3.73A before compensation.

With the lowest DC-link voltage (*Vdc*=50V) of the three STATCOMs, hybrid-STATCOM can still obtain the best compensation results with *DPF*=1.00 and *THDisx*= 3.01%. In addition, the *isx* is reduced to 3.41A from 4.34A after compensation.

TABLE II
SIMULATION RESULTS FOR INDUCTIVE AND CAPACITIVE REACTIVE POWER COMPENSATION OF TRADITIONAL STATCOM, C-STATCOM AND HYBRID-STATCOM

Loading Type	Without and With STATCOM Comp.	i_{sx}(A)	*DPF*	$THDi_{sx}$ (%)	V_{DC}(V)
Case A: inductive and light loading	Before Comp.	6.50	0.83	0.01	--
	Trad. STATCOM	5.55	1.00	7.22	300
	C-STATCOM	5.48	1.00	2.01	80
	Hybrid STATCOM	5.48	1.00	1.98	50
Case B: inductive and heavy loading	Before Comp.	8.40	0.69	0.01	--
	Trad. STATCOM	5.95	1.00	6.55	300
	C-STATCOM	6.30	0.85	17.5	50
	C-STATCOM	5.90	0.98	7.02	300
	Hybrid STATCOM	5.89	1.00	2.10	50
Case C: capacitive loading	Before Comp.	4.34	0.78	0.01	--
	Trad. STATCOM	3.67	1.00	7.61	250
	C-STATCOM	7.10	0.57	23.5	50
	C-STATCOM	5.02	0.99	10.6	500
	Hybrid STATCOM	3.41	1.00	3.01	50

**Shaded areas indicate unsatisfactory results.*

D. Dynamic response of hybrid-STATCOM

Fig. 6 demonstrates the dynamic execution of hybrid-STATCOM for various loadings remuneration. At the point when the load reactive power changes from capacitive to inductive, hybrid-STATCOM takes around one cycle to settle down. In any case, when the load reactive power is changing inside the inductive range, the transient time is altogether decreased and the waveforms are smooth. Meanwhile, the fundamental reactive power is remunerated to around zero notwithstanding amid the transient time. In pragmatic circumstances, the load reactive power at times all of a sudden changes from capacitive to inductive or the other way around, and along these lines hybrid-STATCOM can get great dynamic execution.

As per the simulation results, Table II checks the V-I attributes of the conventional STATCOM, C-STATCOM, and hybrid STATCOM, as appeared in Fig. 2. With comparative remuneration execution, the limit of the active inverter part (or DC-link voltage) of the proposed hybrid-STATCOM is just around 16% of that of customary STATCOM under wide range pay (both inductive and capacitive). As per the cost examine in [14] and [17], the normal cost of conventional STATCOM is around USD $60/kVA, while that of SVC is just roughly $23/kVA. In this manner, by harsh figuring, the normal cost of the proposed hybrid-STATCOM is just about $33/kVA (=$60/kVA*16%+$23/kVA), which is 55% of the normal cost of customary STATCOM. In addition, in light of the fact that the proposed hybrid-STATCOM can dodge the utilization of multilevel structures in medium-voltage level transmission system in contrast with customary STATCOM, the system unwavering quality can be exceedingly expanded and the system control multifaceted nature and operational expenses can be enormously lessened.

Based on the above simulation results, a rundown can be drawn as takes after:

- The customary STATCOM can make up for both inductive and capacitive reactive currents with a high DC-link working voltage because of a little coupling inductor.
- Due to its high DC-link voltage, the conventional STATCOM acquires the poor source current THDisx (caused by switching noise) contrasted and hybrid-STATCOM.
- C-STATCOM has a low DC-link voltage trademark just under a tight inductive loading range. In any case, when the loading current is outside its outlined range, the C-STATCOM requires a high DC-link working voltage because of an expansive coupling capacitor.
- The hybrid-STATCOM gets the best exhibitions of the three STATCOMs under both inductive and capacitive loadings.
- The hybrid-STATCOM has a wide pay extend with low DC-link voltage trademark and great dynamic execution.

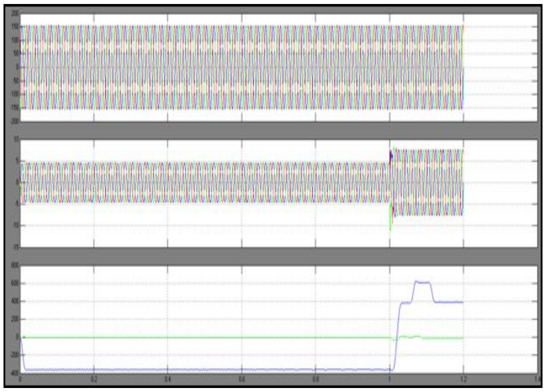
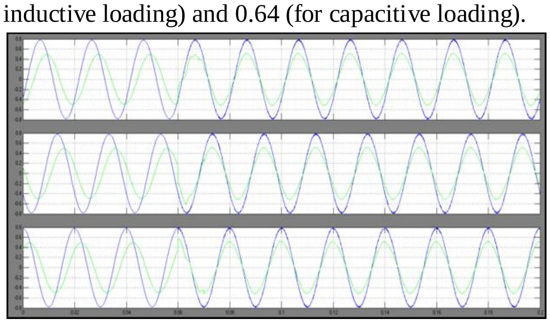


Fig6. Dynamic compensation waveforms of load voltage, source current, and load and source reactive powers by applying hybrid-STATCOM under different loadings cases.

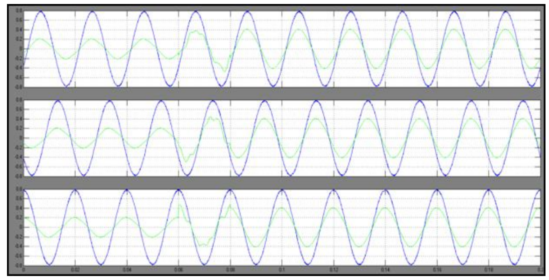
The objective of the is to verify that the proposed hybrid-STATCOM has the characteristics of a wide compensation range and low DC-link voltage under different voltage and current conditions, such as unbalanced current, voltage dip, and voltage fault. The detailed settings of a 110-V, 5-kVA hybrid-STATCOM experimental system are provided in the *Appendix A*, and its DC-link voltage is maintained at *VDC*=50V for all experiments.

Figs. 7 and 8 show the dynamic compensation waveforms of load voltage *vx*, source current *isx*, and reactive power *Qsa* of phase *a* by applying hybrid-STATCOM for inductive load and capacitive load compensation. Fig. 9 gives the corresponding source current harmonic spectrums for inductive and capacitive reactive power compensations.

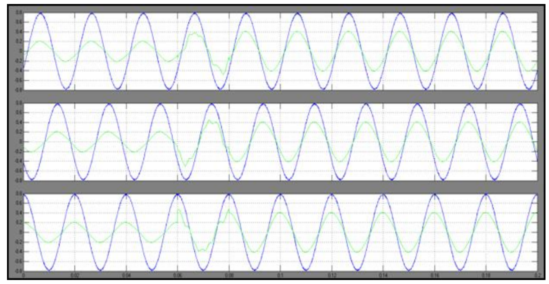
Fig. 7 clearly shows that after hybrid STATCOM compensation, the source current *isx* and the load voltage *vx* are in phase with each other. The source displacement power factors (DPFs) are compensated to 1.00 from the original 0.69 (for inductive loading) and 0.64 (for capacitive loading).



(a)



(b)



(c)

Fig7. Dynamic compensation waveforms of *vx* and *isx* by applying hybrid-STATCOM under (a) inductive load; (b) capacitive load and (c) changing from capacitive load to inductive load.

The worst phase source current *THDisx* are 3.5% and 5.4% after compensation, which satisfy the international standard [24] (*THDisx*<15%). The source currents *isx* are also significantly reduced after compensation. In Figs. 7 (a) and (b), the hybrid-STATCOM obtains a good dynamic compensation performance. In Fig. 7(c), the response time is longer than expected by one cycle because the inductive loads and capacitive loads are manually switching on and off.

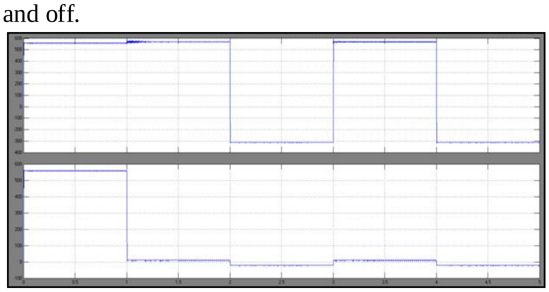


Fig. 8. Dynamic reactive power compensation of *phase a* by applying hybrid-STATCOM.

Figs. 9 and 10 illustrate dynamic compensation waveforms of load voltage *vx* and source current *isx* by applying hybrid-STATCOM under unbalanced loads and voltage fault situations, which clearly verify its good dynamic performance.

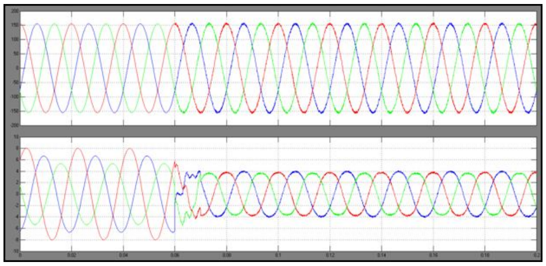


Fig9. Dynamic compensation waveforms of *vx* and *isx* by applying hybrid-STATCOM under unbalanced loads.

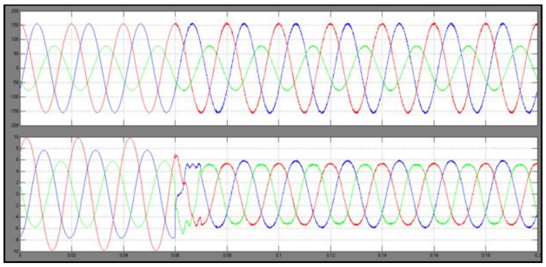


Fig10. Dynamic compensation waveforms of *vx* and *isx* by applying hybrid-STATCOM under voltage fault condition.

Fig. 19 shows that the proposed hybrid-STATCOM can compensate for and balance the source current even under unbalanced loads with low *VDC*=50V. The unbalanced *isx* are compensated from 4.80A, 3.83A, and 5.74A to 2.94A, 2.79A, and 2.86A, respectively. The DPF and *THDisx* are compensated to unity and lower than 9.0%, which satisfy the international standard [24]. From Fig. 12, it can be seen that the proposed hybrid-STATCOM can still obtain satisfactory performances even under asymmetric grid fault. During the voltage fault, the *isx* can be compensated to be approximately balanced with DPF≈1 and *THDisx*<10.0%.

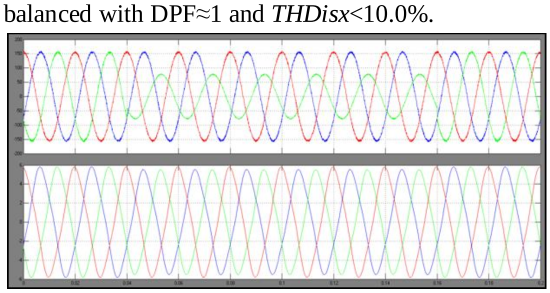


Fig. 11. Dynamic compensation waveforms of *vx* and *isx* by applying hybrid-STATCOM during voltage dip.

Fig. 11 also provides the dynamic compensation waveforms of load voltage *vx* and source current *isx* by applying hybrid-STATCOM during a sudden voltage dip. It is found that hybrid-STATCOM can obtain good dynamic and reactive power compensation performances.

Table III summarizes the hybrid STATCOM experimental results. The above experimental results confirm that the hybrid-STATCOM has a wide reactive power compensation range and low DC-link voltage characteristics with good dynamic performance even under different voltage and current conditions.

TABLE III
EXPERIMENTAL COMPENSATION RESULTS BY HYBRID-STATCOM (VDC= 50V) UNDER DIFFERENT SYSTEM AND LOADING SITUATIONS

Different Situations	Comp.	i_{sx}(A)			*DPF*			$THDi_{sx}$ (%)		
		A	B	C	A	B	C	A	B	C
Inductive load	Before	7.13	7.14	7.34	0.69	0.70	0.70	1.1	1.2	1.2
	After	4.79	4.97	4.95	1.00	1.00	1.00	3.5	3.3	3.3
Capacitive load	Before	3.60	3.63	3.65	0.65	0.64	0.64	3.1	2.9	2.8
	After	2.92	2.80	2.85	1.00	1.00	1.00	5.4	5.4	5.2
Unbalanced loads	Before	4.80	3.83	5.74	0.36	0.69	0.64	2.0	1.4	1.2
	After	2.94	2.79	2.86	1.00	1.00	1.00	5.9	8.7	8.1
Voltage fault	Before	5.57	4.18	7.06	0.67	0.38	0.87	2.3	2.5	1.6
	After	4.30	3.98	4.00	0.99	1.00	0.99	4.7	9.3	6.2

CONCLUSION

In this paper, a hybrid-STATCOM in three-phase power system has been proposed and talked about as a practical reactive power compensator for medium voltage level application. The system configuration and V– I normal for the hybrid-STATCOM were dissected, talked about, and contrasted and conventional STATCOM and C-STATCOM. What's more, its parameter plan technique was proposed on the premise of consideration of the reactive power remuneration range and avoidance of a potential reverberation issue. Additionally, the control technique of the hybrid-STATCOM was produced under various voltage and current conditions. At long last, the wide pay range and low dc-link voltage attributes with great dynamic execution of the hybrid-STATCOM were demonstrated by both simulation and exploratory results.

APPENDIX
SETTINGS OF SIMULATIONS AND EXPERIMENTS

Table IV shows the simulation system parameters for traditional STATCOM, C STATCOM, and hybrid-STATCOM under different testing loads. For experimental purposes, a 110-V, 5-kVA experimental prototype of the three-phase hybrid-STATCOM is constructed in the laboratory.

The control system has a sampling frequency of 25 kHz. The switching devices for the active inverter are Mitsubishi IGBTs PM300DSA060. The switching devices for the TCLC are thyristors SanRex PK110FG160. Moreover, the experimental parameters of the hybrid-STATCOM are the same as those for the simulation listed in Table IV.

TABLE IV
SIMULATION AND EXPERIMENTAL PARAMETERS FOR TRADITIONAL STATCOM, C-STATCOM, AND HYBRID-STATCOM

	Parameters	Physical values
System parameters	v_x, f, L_s	110 V, 50 Hz, 0.1 mH
Traditional STATCOM	L	5 mH
C-STATCOM	L, C	5 mH, 80 uF
Hybrid-STATCOM	L_c, L_{PF}, C_{PF}	5 mH, 30 mH, 160 uF
Case *A*: inductive and light loading	L_{L1}, R_{L1}	30 mH, 14 Ω
Case *B*: inductive and heavy loading	L_{L2}, R_{L2}	30 mH, 9 Ω
Case *C*: capacitive loading	C_{L3}, R_{L3}	200 uF, 20 Ω

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