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A NEW CONTROL STRATEGY FOR HYBRID STATCOM WITH WIDE COMPENSATION RANGE AND 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 compensation range and low DC-link voltage. Because of these prominent characteristics, the system costs can be greatly reduced. In this paper, the circuit configuration of hybrid-STATCOM is introduced first. Its V-I characteristic is then analyzed, discussed, and compared with traditional STATCOM and capacitive-coupled STATCOM (C-STATCOM). The system parameter design is then proposed on the basis of consideration of the reactive power compensation range and avoidance of the potential resonance problem. After that, a control strategy for hybrid-STATCOM is proposed to allow operation under different voltage and current conditions, such as unbalanced current, voltage dip, and voltage fault. Finally, simulation and experimental results are provided to verify the wide compensation range and low DC-link voltage characteristics and the good dynamic performance of the proposed hybrid-STATCOM

***Keywords*:** Capacitive-coupled static synchronous compensator (C-STATCOM), hybrid-STATCOM, low dc-link voltage, STATCOM, wide compensation range.

I. Introduction

The large reactive current in transmission systems is one of the most common power problems that increases transmission losses and lowers the stability of a power system [1]-[19]. Application of reactive power compensators is one of the solutions for this issue.

Static VAR compensators (SVCs) are traditionally used to dynamically compensate reactive currents as the loads vary from time to time. However, SVCs suffer from many problems, such as resonance problems, harmonic current injection, and slow response [2]-[3]. To overcome these disadvantages, static synchronous compensators (STATCOMs) and active power filters (APFs) were developed for reactive current compensation with faster response, less harmonic current injection, and better performance [4]-[9]. However, the STATCOMs or APFs usually require multilevel structures in a medium- or high-voltage level transmission system to reduce the high-voltage stress across each power switch and DC-link capacitor, which drives up the initial and operational costs of the system and also increases the control complexity. Later, series-type capacitive-coupled STATCOMs (C-STATCOMs) were proposed to reduce the system DC-link operating voltage requirement [10], and other series-type hybrid structures that consist of different passive power filters (PPFs) in series with STATCOMs or APF structures (PPF-STATCOMs) have been applied to power distribution systems [11]-[16] and traction power systems [17]-[19]. However, C-STATCOMs and other series-type PPF-STATCOMs contain relatively narrow reactive power compensation ranges. When the required compensating reactive power is outside their compensation ranges, their system performances can significantly deteriorate.

To improve the operating performances of the traditional STATCOMs, C-STATCOMs, and other PPF-STATCOMs, many different control techniques have been proposed, such as the instantaneous p-q theory [4], [10], [11], [17]-[19], the instantaneous d-q theory [5], [6], [14], the instantaneous id-iq method [7], negative- and zero-sequence control [8], the back propagation (BP) control method [9], nonlinear control [12], Lyapunov-function-based control [13], instantaneous symmetrical component theory [15], and hybrid voltage and current control [16].

To reduce the current rating of the STATCOMs or APFs, a hybrid combination structure of PPF in parallel with STATCOM (PPF// STATCOM) was proposed in [20] and [21]. However, this hybrid compensator is dedicated for inductive loading operation. When it is applied for capacitive loading compensation, it easily loses its small active inverter rating characteristics. To enlarge the compensation range and keep low current rating characteristic of 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 eliminate the harmonics and compensate for the small amounts of load reactive and unbalanced power left by the SVC. However, if this structure is applied in a medium- or high-voltage level transmission system, the APF still requires a costly voltage step-down transformer and/or multilevel

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structure. In addition, these two parallel connected-hybrid STATCOM structures [15]-[17] may suffer from a resonance problem.

To overcome the shortcomings of different reactive power compensators [1]-[22] for transmission systems, this paper proposes a hybrid-STATCOM that consists of a thyristor-controlled LC part (TCLC) and an active inverter part, as shown in Fig. 1. The TCLC part provides a wide reactive power compensation range and a large voltage drop between the system voltage and the inverter voltage so that the active inverter part can continue to operate at a low DC-link voltage level. The small rating of the active inverter part is used to improve the performances of the TCLC part by absorbing the harmonic currents generated by the TCLC part, avoiding mistuning of the firing angles, and preventing the resonance problem. The contributions of this paper are summarized as follows.

- Its V-I characteristic is analyzed to provide a clear view of the advantages of hybrid-STATCOM in comparison with traditional STATCOM and C-STATCOM.
- Its parameter design method is proposed based on consideration of the reactive power compensation range, prevention of the potential resonance problem and avoidance of mistuning of firing angle.
- A new control strategy for hybrid-STATCOM is proposed to coordinate the TCLC part and the active inverter part for reactive power compensation under different voltage and current conditions, such as unbalanced current, voltage fault, and voltage dip.

The characteristics of different reactive power compensators and the proposed hybrid-STATCOM for the transmission system are compared and summarized in Table I.

Table 1.1

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

II. Active Power Filter:

2.1 Introduction to APF:

Harmonic distortion in power distribution systems can be suppressed mainly by, passive and active filtering. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion. The uses of passive elements do not always respond correctly to the dynamics of the power distribution systems. Passive filters are known to cause resonance, thus affecting the stability of the power distribution systems. Frequency variation of the power distribution system and tolerances in components values affect the passive filtering characteristics. As the regulatory requirements become more stringent, the passive filters might not be able to meet future revisions of a particular Standard. This may required a retrofit of new filters.

Remarkable progress in power electronics had spurred interest in Active Power Filters (APF) for harmonic distortion mitigation. Active filtering is a relatively new technology, practically less than four decades old. The basic principle of APF is to utilize power electronics technologies to produce specific current components that cancel the harmonic current components caused by the nonlinear load.

APFs have a number of advantages over the passive filters. First of all, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the APFs performances are independent on the power distribution system properties. Active filtering is a relatively new technology, practically less than four decades old. There is still a need for further research and development to make this technology well established.

2.2 Development of APF's:

The technology of active power filter has been developed during the past two decades reaching maturity for harmonics compensation, reactive

2.3 Current source inverters:

The current-fed PWM inverter bridge structure behaves as a non sinusoidal current source to meet the harmonic current requirement of the nonlinear load. It has a self-supported dc reactor that ensures the continuous circulation of the dc current. They present good reliability, but have important losses and require higher values of parallel capacitor filters at the ac terminals to remove unwanted current harmonics. Moreover, they cannot be used in multilevel or multistep modes configurations to allow compensation in higher power ratings.

2.4 Voltage source inverter:

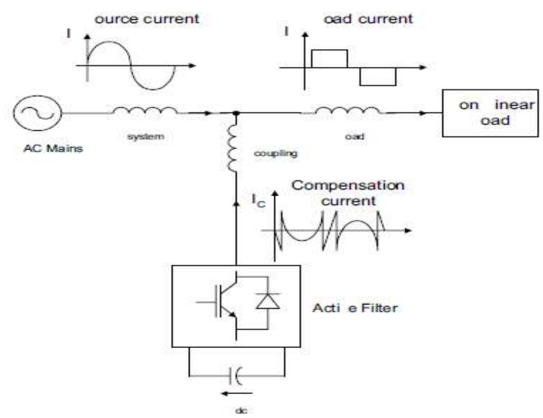
The other converter used in active power filter topologies is the voltage-source PWM inverter. This converter is more convenient for active power filtering applications since it is lighter, cheaper, and expandable to multilevel and multistep versions, to improve its performance for high power rating compensation with lower switching frequencies. The PWM voltage source inverter has to be connected to the ac mains through coupling reactors. An electrolytic capacitor keeps a dc voltage constant and ripple free.

2.5 Classification of APF's

Active power filters can be classified based on the type of converter, topology, control scheme, and compensation characteristics. The most popular classification is based on the topology such as shunt, series or hybrid. The hybrid configuration is a combination of passive and active compensation. Shunt active power filters are widely used to compensate current harmonics, reactive power and load current unbalanced. It can also be used as a static var generator in power system networks for stabilizing and improving voltage profile. Series active power filters is connected before the load in series with the ac mains, through a coupling transformer to eliminate voltage harmonics and to balance and regulate the terminal voltage of the load or line.

2.6 Shunt Active Power Filters:

Shunt active power filters compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this case, the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180_. As a result, components of harmonic currents contained in the load current are cancelled by the effect of the active filter, and the source current remains sinusoidal and in phase with the respective phase to neutral voltage. This principle is applicable to any type of load considered as an harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution



Compensation characteristics of a shunt active power filter Power Circuit Topologies

Shunt active power filters are normally implemented with PWM voltage-source inverters. In this type of application, the PWM-VSI operates as a current-controlled voltage-source. Traditionally, levels PWM-VSI have been used to implement such system connected to the ac bus through a transformer. This type of configuration is aimed to compensate nonlinear load rated in the medium power range (hundreds of kVA) due to semiconductors rated values limitations. However, in the last years multilevel PWM voltage-source inverters have been proposed to develop active power filters for medium voltage and higher rated power applications. Also, active power filters implemented with multiples of VSI connected in parallel to a dc bus but in series through a transformer or in cascade have been proposed in the technical literature. The use of VSI connected in cascade is an interesting alternative to compensate high power nonlinear loads. The use of two PWM-VSI with different rated power allows the use of different switching frequencies, reducing switching stresses and commutation losses in the overall compensation system.

The voltage-source inverter connected closer to the load compensates for the displacement power factor and lower frequency current harmonic components while the second compensates only high frequency current harmonic components. The first converter requires higher rated power than the second and can operate at lower switching frequency. The compensation characteristics of the cascade shunt active power filter .In recent years, there has been an increasing interest in using multilevel inverters for high power energy conversion, specially for drives and reactive power compensation.

The use of neutral-point-clamped (NPC) inverters allows equal voltage shearing of the series connected semiconductors in each phase. Basically, multilevel inverters have been developed for applications in medium voltage ac motor drives and static var compensation. For these types of applications, the output voltage of the multilevel inverter must be able to generate an almost sinusoidal output current. In order to generate a near sinusoidal output current, the output voltage should not contain low frequency harmonic components. However, for active power filter applications the three level NPC inverter output voltage must be able to generate an output current that follows the respective reference current containing the harmonic and reactive component required by the load. Currents and voltage waveforms obtained for a shunt active power filter implemented with a three-level NPC-VSI.**3.**

III. Static Synchronous Compensator (STATCOM)

3.1 Introduction:

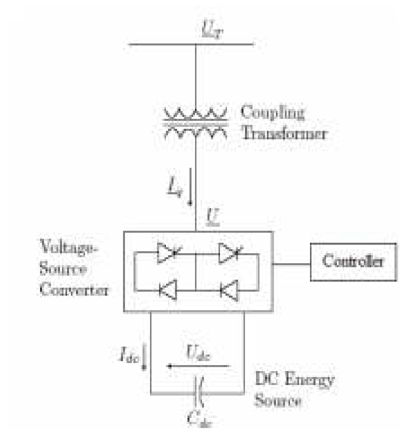
The STATCOM is a solid-state-based power converter version of the SVC. Operating as a shunt-connected SVC, its capacitive or inductive output currents can be controlled independently from its terminal AC bus voltage. Because of the fast-switching characteristic of power converters, STATCOM provides much faster response as compared to the SVC. In addition, in the event of a rapid change in system voltage, the capacitor voltage does not change instantaneously; therefore, STATCOM effectively reacts for the desired responses. For example, if the system voltage drops for any reason, there is a tendency for STATCOM to inject capacitive power to support the dipped voltages.

STATCOM is capable of high dynamic performance and its compensation does not depend on the common coupling voltage. Therefore, STATCOM is very effective during the power system disturbances.

Moreover, much research confirms several advantages of STATCOM. These advantages compared to other shunt compensators include:

• Size, weight, and cost reduction
• Equality of lagging and leading output
• Precise and continuous reactive power control with fast response
• Possible active harmonic filter capability

This chapter describes the structure, basic operating principle and characteristics of STATCOM. In addition, the concept of voltage source converters and the corresponding control techniques are illustrated.



Block Diagram of STATCOM

3.2 Control of STATCOM:

The controller of a STATCOM operates the converter in a particular way that the phase angle between the converter voltage and the transmission line voltage is dynamically adjusted and synchronized so that the STATCOM generates or absorbs desired VAR at the point of coupling connection. Figure 3.4 shows a simplified diagram of the STATCOM with a converter voltage source 1E and a tie reactance, connected to a system with a voltage source, and a The venin reactance, XTIEX_THV$_{TH}$.

Current Controlled STATCOM:

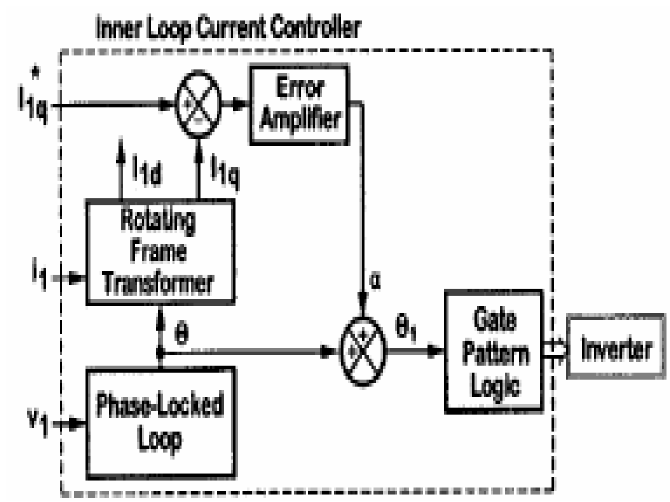
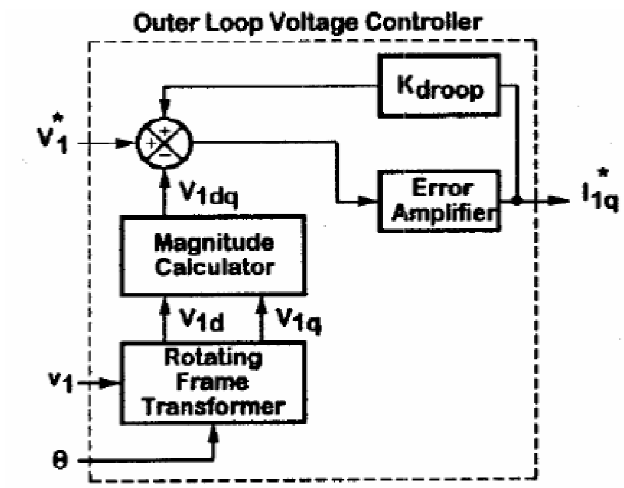


Figure above shows the reactive current control block diagram of the STATCOM. An instantaneous three-phase set of line voltages, v_l, at BUS 1 is used to calculate the reference angle, θ, which is phase-locked to the phase a of the line voltage, v_{la} . An instantaneous three-phase set of measured converter currents, i_l, is decomposed into its real or direct component, I_{1d}, and reactive or quadrature component, I_{1q}, respectively. The quadrature component is compared with the desired reference value, I_{1q}^* and the error is passed through an error amplifier which produces a relative angle, α, of the converter voltage with respect to the transmission line voltage. The phase angle, θ_1, of the converter voltage is calculated by adding the relative angle, α, of the converter voltage and the phase lock-loop angle, θ. The reference quadrature component.

3.3 Voltage Controlled STATCOM:

In regulating the line voltage, an outer voltage control loop must be implemented. The outer voltage control loop would automatically determine the reference reactive current for the inner current control loop which, in turn, will regulate the line voltage

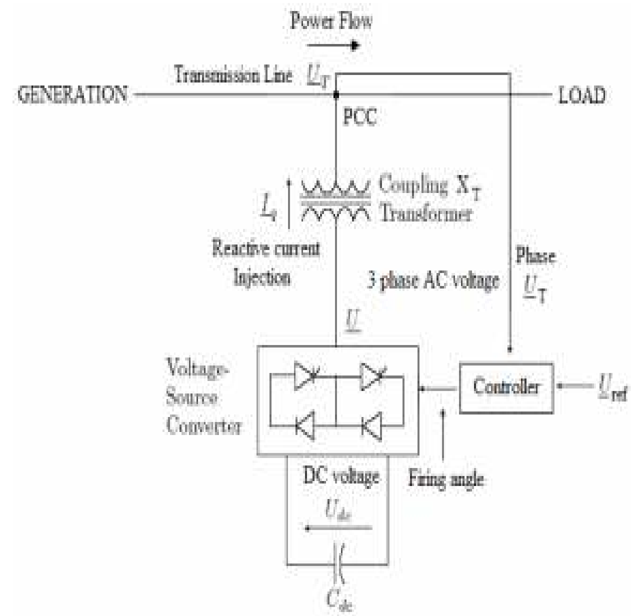


Voltage control block diagram of the STATCOM.

An instantaneous three-phase set of measured line voltages, v_1, at BUS 1 is decomposed into its real or direct component, V_{1d}, and reactive or quadrature component, V_{1q}, is compared with the desired reference value, V_1^*, (adjusted by the droop factor, K_{droop}) and the error is passed through an error amplifier which produces the reference current, I_{1q}^*, for the inner current control loop. The droop factor, K_{droop}, is defined as the allowable voltage error at the rated reactive current flow through the STATCOM.

Basic operating principles of STATCOM:

The STATCOM is connected to the power system at a PCC (point of common coupling), through a step-up coupling transformer, where the voltage-quality problem is a concern. The PCC is also known as the terminal for which the terminal voltage is U_T. All required voltages and currents are measured and are fed into the controller to be compared with the commands. The controller then performs feedback control and outputs a set of switching signals (firing angle) to drive the main semiconductor switches of the power converter accordingly to either increase the voltage or to decrease it accordingly. A STATCOM is a controlled reactive-power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks. Using the controller, the VSC and the coupling transformer, the STATCOM operation is illustrated in Figure below.



STATCOM operation in a power system

The charged capacitor C_{dc} provides a DC voltage, U_{dc} to the converter, which produces a set of controllable three-phase output voltages, U in synchronism with the AC system. The synchronism of the three-phase output voltage with the transmission line voltage has to be performed by an external controller. The amount of desired voltage across STATCOM, which is the voltage reference, Uref, is set manually to the controller. The voltage control is thereby to match U_T with Uref which has been elaborated. This matching of voltages is done by varying the amplitude of the output voltage U, which is done by the firing angle set by the controller. The controller thus sets U_T equivalent to the Uref. The reactive power exchange between the converter and the AC system can also be controlled. This reactive power exchange is the reactive current injected by the STATCOM, which is the current from the capacitor produced by absorbing real power from the AC system.

$$I_{-q} = \frac{U_{-T} - U_{-eq}}{X_{eq}}$$

Where I_q is the reactive current injected by the STATCOM

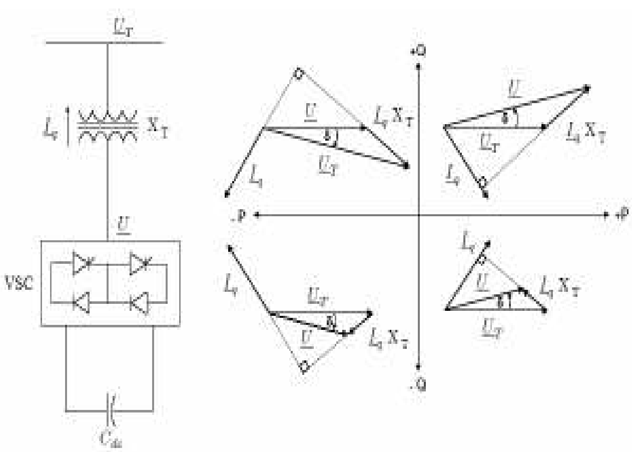
U_T is the STATCOM terminal voltage

U_{eq} is the equivalent Thevenin voltage seen by the STATCOM

X_{eq} is the equivalent Thevenin reactance of the power system seen by the STATCOM

If the amplitude of the output voltage U is increased above that of the AC system voltage, U_T, a leading current is produced, i.e. the STATCOM is seen as a conductor by the AC system and reactive power is generated. Decreasing the amplitude of the output voltage below that of the AC system, a lagging current results and the STATCOM is seen as an inductor. In this case reactive power is absorbed. If the amplitudes are equal no power exchange takes place.

A practical converter is not lossless. In the case of the DC capacitor, the energy stored in this capacitor would be consumed by the internal losses of the converter. By making the output voltages of the converter lag the AC system voltages by a small angle, δ, the converter absorbs a small amount of active power from the AC system to balance the losses in the converter. The diagram in Figure below illustrates the phasor diagrams of the voltage at the terminal, the converter output current and voltage in all four quadrants of the PQ plane.



Phasor diagrams for STATCOM applications

The mechanism of phase angle adjustment, angle δ, can also be used to control the reactive power generation or absorption by increasing or decreasing the capacitor voltage U_{dc}, with reference with the output voltage U.

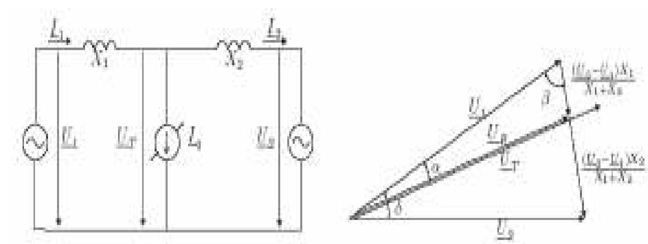
Instead of a capacitor a battery can also be used as DC energy. In this case the converter can control both reactive and active power exchange with the AC system. The capability of controlling active as well as reactive power exchange is a significant feature which can be used effectively in applications requiring power oscillation damping, to level peak power demand, and to provide uninterrupted power for critical load.

IV.CHARACTERISTICS OF STATCOM:

The derivation of the formula for the transmitted active power employs considerable calculations. Using the variables defined in Figure below and applying Kirchhoff's laws the following equations can be written;

$$I_{-2} = \frac{U_{-T} - U_{-2}}{jX_2} = \frac{(U_{-1} - jI_{-1}X_1) - U_{-2}}{jX_2}$$

$$I_{-2} = I_{-1} - I_{-q}$$



Two machine system with STATCOM

V. Functional requirements of STATCOM:

The main functional requirements of the STATCOM in this thesis are to provide shunt compensation, operating in capacitive mode only, in terms of the following;

• Voltage stability control in a power system, as to compensate the loss voltage along transmission. This compensation of voltage has to be in synchronism with the AC system regardless of disturbances or change of load.

• Transient stability during disturbances in a system or a change of load

• Direct voltage support to maintain sufficient line voltage for facilitating increased reactive power flow under heavy loads and for preventing voltage instability

• Reactive power injection by STATCOM into the system

The design phase and implementation phase (as presented in the next chapter) would refer to the theoretical background of STATCOM in providing the requirement.

VI. Parameter Design of Hybrid-STATCOM:

The proposed TCLC part is a newly proposed SVC structure which designed based on the basis of the consideration of the reactive power compensation range (for L_{pf} and C_{pf}) and the prevention of the potential resonance problem (for L_c). The active inverter part (DC-link voltage V_{DC}) is designed to avoid mistuning of the firing angle of TCLC part.

6.1 Design of C_{PF} and L_{PF}:

The purpose of the TCLC part is to provide the same amount of compensating reactive power $Q_{cx,TCLC}(\alpha_x)$ as the reactive power required by the loads Q_{Lx} but with the opposite direction. Therefore, C_{PF} and L_{PF} are designed on the basis of the maximum capacitive and inductive reactive power. The compensating reactive power Q_{cx} range in term of TCLC impedance $X_{TCLC}(\alpha_x)$ can be expressed as

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

where V_x is the RMS value of the load voltage and $X_{TCLC}(\alpha_x)$ is the impedance of the TCLC part, which can be obtained from (4). In (9), when the $X_{TCLC}(\alpha_x)=X_{Cap}(min)(\alpha_x =180^o)$ and $X_{TCLC}(\alpha_x)=X_{Ind}(min)(\alpha_x =90^o)$, the TCLC part provides the maximum capacitive and inductive compensating reactive power $Q_{cx(MaxCap)}$ and $Q_{cx(MaxInd)}$, 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 $X_{Ind}(min)$ and the capacitive impendence $X_{Cap}(min)$ are obtained from (5) and(6), respectively.

To compensate for the load reactive power (Q_{cx} =- Q_{Lx}), C_{PF} and L_{PF} can be deduced on the basis of the loading maximum inductive reactive power $Q_{Lx(MaxInd)}$ (=-$Q_{cx(MaxCap)}$) and capacitive reactive power $Q_{Lx(MaxCap)}$ (=-$Q_{cx(MaxInd)}$). Therefore, based on (10) and (11), the parallel capacitor C_{PF} and inductor L_{PF} can be designed as

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

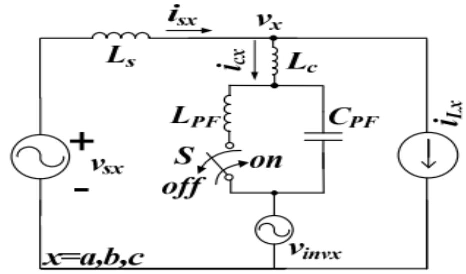
$$L_{PF} = \frac{V_x^2 + \omega L_c Q_{Lx(MaxCap)}}{-\omega Q_{Lx(MaxCap)} + \omega^3 L_c C_{PF} Q_{Lx(MaxCap)} + \omega^2 V_x^2 C_{PF}} \quad (13)$$

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

6.1 Design of L_C:

For exciting resonance problems, a sufficient level of harmonic source voltages or currents must be present at or near the resonant frequency. Therefore, L_c can be designed to tune the resonance points to diverge from the dominated harmonic orders d n6n ±= 1th (n=1, 2, 3…) of a three-phase three-wire transmission system to avoid the resonance problem.

The thyristors (T_{x1} and T_{x2}) for each phase of the TCLC part can be considered as a pair of bidirectional switches that generate low-order harmonic currents when the switches change states.



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

Referring to Fig. 3, when switch S is turned off, the TCLC part can be considered as the L_c in series with C_{PF}, which is called LC-mode. In contrast, when switch S is turned on, the TCLC can be considered as the L_c in series with the combination of C_{PF} in parallel with L_{PF}, which is called LCL-mode. 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 expressed as

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

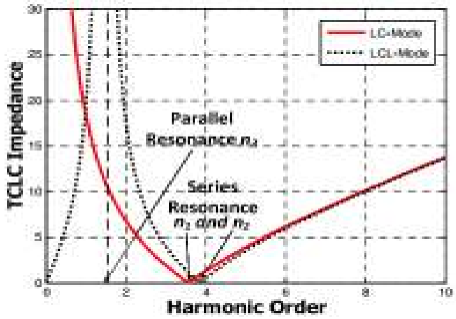
$$X_{LCL,n}(n) = \left| \frac{n\omega(L_c + L_{PF}) - (n\omega)^3 L_{PF} L_c C_{PF}}{1-(n\omega)^2 L_{PF} C_{PF}} \right| \quad (15)$$

In (14) and (15), there are two series resonance points n1 at $X_{LC},n(n_1)=0$ and n_2 at $X_{LCL},n(n_2)=0$ and a parallel resonance point n_3 at $X_{LCL},n(n_3)= +\infty$. L_c can be designed to tune the resonance points n_1 and n_2 to diverge from the dominated harmonic orders d = ±1n6nth (n=1, 2, 3…) or approach the 3nth order in a three-phase three-wire system. Based on the above discussion, the design criteria of L_c can be expressed as

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

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

they can be satisfied simultaneously as long as n_1 and n_2 are away from the dominated harmonic orders nd. The designed C_{PF} and L_{PF} should also satisfy (17). In this paper, n_1 = 3.6, n_2 =3.9, and n_3=1.5 are chosen.



TCLC impedance under different harmonic order.

6.2 Design of V_{DC}:

Different with the traditional V_{DC} design method of the STATCOM to compensate maximum load reactive power, the V_{DC} 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. Reforming (3), the inverter voltage V_{invx} can also be expressed as

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

where Q_{Lx} is the load reactive power, $Q_{cx,TCLC}(\alpha_x)$ is the TCLC part compensating reactive power, and V_x is the RMS value of the load voltage. Combing (18) with $V_{DC} = 6V_{invx}$, the required DC-link voltage V_{DC} 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, $Q_{cx,TCLC}(\alpha_x)$ is controlled to be equal to $-Q_{Lx}$ so that the required V_{DC} can be zero. However, in the practical case, the $Q_{cx,TCLC}(\alpha_x)$ may not be exactly equal to $-Q_{Lx}$ due to the firing angle mistuning problem. The worst case of mistuning $Q_{Lx}/Q_{cx,TCLC}(\alpha_x)$ ratio can be pre-measured to estimate the required minimum V_{DC} value. Finally, a slightly greater V_{DC} value can be chosen.

Based on (12), (13), (16), and (19), the system parameters C_{PF}, L_{PF}, L_c, and VDC of hybrid-STATCOM can be designed accordingly. In the following section, the control strategy of hybrid-STATCOM is proposed and discussed.

VII. Control Strategy of Hybrid-STATCOM:

In this section, a control strategy for hybrid-STATCOM is proposed by coordinating the control of the TCLC part and the active inverter part so that the two parts can complement each other's disadvantages and the overall performance of hybrid-STATCOM can be improved. Specifically, with the proposed controller, the response time of hybrid-STATCOM can be faster than SVCs, and the active inverter part can operate at lower dc-link operating voltage than the traditional STATCOMs. The control strategy of hybrid-STATCOM is separated into two parts for discussion: A. TCLC part control and B. Active inverter part control. The response time of hybrid-STATCOM is discussed in part C. The control block diagram of hybrid-STATCOM is shown in Fig. 5.

7.1 TCLC part control:

Different with the traditional SVC control based on the traditional definition of reactive power [2]-[3], to improve its response time, the TCLC part control is based on the instantaneous pq theory [4]. The TCLC part is mainly used to compensate the reactive current with the controllable TCLC part impedance X_{TCLC}. Referring to (3), to obtain the minimum inverter voltage invx≈0V , X_{TCLC} can be calculated with Ohm's law in terms of the RMS values of the load voltage (V_x) and the load reactive current (I_{Lqx}). However, to calculate the X_{TCLC} in real time, the expression of XTCLC can be rewritten in terms of instantaneous values as

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

Where v is the norm of the three-phase instantaneous load voltage and q_{Lx} is the DC component of the phase reactive power. The real-time expression of v and q_{Lx} 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), v_x and q_{Lx} are the instantaneous load voltage and the load reactive power, respectively. As shown in Fig. 5, a limiter is applied to limit the calculated X_{TCLC} in (9) within the range of $X_{TCLC}>X_{ind}(min)$ and $X_{TCLC}<X_{Cap}(min)$ ($X_{Cap}(min)<0$). With the calculated X_{TCLC}, the firing angle α_x can be determined by solving (4). Because (4) is complicated, a look-up table (LUT) is installed inside the controller. The trigger signals to control the TCLC part can then be generated by comparing the firing angle α_x with θ_x, which is the phase angle of the load voltage v_x. θ_x can be obtained by using a phase lock loop (PLL). Note that the firing angle of each phase can differ if the unbalanced loads are connected (see (4) and (20)). With the proposed control algorithm, the reactive power of each phase can be compensated and the active power can be basically balanced, so that DC-link voltage can be maintained at a low level even under unbalanced load compensation.

7.1 Active inverter part control:

In the proposed control strategy, the instantaneous active and reactive current i_d-i_q method [7] is implemented for the active inverter part to improve the overall performance of hybrid-STATCOM under different voltage and current conditions, such as balanced/unbalanced, voltage dip, and voltage fault. Specifically, the active inverter part is used to improve the TCLC part characteristic by limiting the compensating current i_{cx} to its reference value i_{cx}* so that the mistuning problem, the resonance problem, and the harmonic injection problem can be avoided. The i_{cx}* is calculated by applying the i_d-i_q method [7] because it is valid for different voltage and current conditions.

The calculated i_{cx}* contains reactive power, unbalanced power, and current harmonic components. By controlling the compensating current i_{cx} to track its reference i_{cx}*, the active inverter part can compensate for the load harmonic currents and improve the reactive power compensation ability and dynamic performance of the TCLC part under different voltage conditions. The i_{cx}* can be calculated as

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

where i_d and i_q are the instantaneous active and reactive current, which include DC components i_d and i_q , and AC components ~ i_d and ~ i_q . ~ i_d is obtained by passing i_d through a high-pass filter. i_d and i_q 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

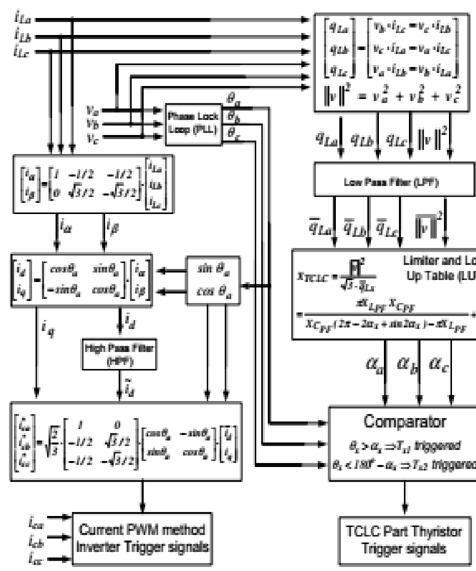
$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (25)$$

Where i_{Lx} is the load current signal.

7.2 Response time of hybrid-STATCOM:

The TCLC part has two back-to-back connected thyristors in each phase that are triggered alternately in every half cycle, so that the control period of the TCLC part is one cycle (0.02 s). However, the proposed hybrid-STATCOM structure connects the TCLC part in series with an instantaneous operated active inverter part, which can significantly improve its overall response time. With the proposed controller, the active inverter part can limit the compensating current i_{cx} to its reference value i_{cx}* via pulse width modulation (PWM) control, and the PWM control frequency is set to be 12.5 kHz. During the transient state, the response time of hybrid-STATCOM can be separately discussed in the following two cases. a) If the load reactive power is dynamically changing within the inductive range (or within the capacitive range), the response time of hybrid-STATCOM can be as fast as traditional STATCOM. b) In contrast, when the load reactive power suddenly changes from capacitive to inductive or vice versa, the hybrid-STATCOM may take approximately one cycle to settle down. However, in practical application, case b) described above seldom happens. Therefore, based on the above discussion, the proposed hybrid-STATCOM can be considered as a fast-response reactive power compensator in which the dynamic performances of hybrid-STATCOM are proved by the simulation result (Fig. 6) and the experimental results (Fig. 7, Fig. 8, Fig. 10, and Fig. 12).

The following section reports the simulation and experimental results to verify the above V-I characteristics analysis and the control strategy of the hybrid-STATCOM in comparison with traditional STATCOM and C-STATCOM.



The control block diagram of hybrid-STATCOM

VIII. Simulation Results

In this section, the simulation results among traditional STATCOM, C-STATCOM, and the proposed hybrid-STATCOM are discussed and compared. The previous discussions of the required inverter voltages (or DC-link voltage dc ··= V32V $_{invx}$) for these three STATCOMs are also verified by simulations. The STATCOM+s are simulated with the same voltage level as in the experimental results in Section VI. The simulation studies are carried out with PSCAD/EMTDC. Table IV in the Appendix A shows the simulation system parameters for traditional STATCOM, C-STATCOM, and hybrid-STATCOM. In addition, three different cases of loading are built for testing: A. inductive and light loading, B. inductive and heavy loading, and C. capacitive loading. These three testing cases are also represented by points A, B, and C in Fig. 2. The detailed simulation results are summarized in Table II. Finally, the dynamic response of hybrid-STATCOM is simulated and discussed in this section part D. With the consideration of IEEE standard 519-2014 [24], total demand distortion (TDD) =15% and ISC/IL in 100<1000 scale at a typical case, the nominal rate current is assumed to be equal to the fundamental load current in the worst-case analysis, which results in THD=TDD=15%. Therefore, this paper evaluates the compensation performance by setting THD<15%.

8.1 Inductive and light loading:

When the loading is inductive and light, traditional STATCOM requires a high DC-link voltage (V_{dc}> ·V_2 −LL =269V, V_{dc}=300V) for compensation. After compensation, the source current isx is reduced to 5.55A from 6.50A and the source-side displacement power factor (DPF) becomes unity from 0.83. In addition, the source current total harmonics distortion (THD_{isx}) is 7.22% after compensation, which satisfies the international standard [24] (THD_{isx}<15%).

For C-STATCOM, the coupling impedance contributes a large voltage drop between the load voltage and the inverter voltage so that the required DC-link voltage can be small (V_{dc}=80V). The i_{sx}, DPF and THD_{isx} are compensated to 5.48A, unity, and 2.01%, respectively.

For the proposed hybrid-STATCOM, the i_{sx}, DPF, and THD_{isx} are compensated to 5.48A, unity, and 1.98%, respectively. As discussed in the previous section, a low DC-link voltage (V_{dc}=50V) of hybrid-STATCOM is used to avoid mistuning of firing angles, prevent resonance problems, and reduce the injected harmonic currents.

8.2 Inductive and heavy loading:

To compensate for the inductive and heavy loading, traditional STATCOM still requires a high DC-link voltage of V_{dc}=300V for compensation. Traditional STATCOM can obtain acceptable results (DPF = 1.00 and THD_{isx} = 6.55%). The isx is reduced to 5.95A from 8.40A after compensation.

With a low DC-link voltage (V_{dc}=50V), C-STATCOM cannot provide satisfactory compensation results (DPF = 0.85 and THD_{isx} = 17.5%). However, when the DC-link voltage is increased to V_{dc}=300V, the compensation results (DPF = 1.00 and THD_{isx}= 7.02%) are acceptable and satisfy the international standard [24] (THD_{isx}<15%). The i_{sx} is reduced to 5.90A from 8.40A after compensation.

On the other hand, the proposed hybrid-STATCOM can still obtain acceptable compensation results (DPF = 1.00 and THD_{isx} = 3.01%) with a low DC-link voltage of V_{dc}=50V. The i_{sx} is reduced to 5.89A from 8.40A after compensation.

8.2 Capacitive loading:

When the loading is capacitive, with V_{dc}=250V (V_{dc}< −LL =· V269V2), the compensation results of traditional STATCOM are acceptable, in which the DPF and THD_{isx} are compensated to unity and 7.61%. The i_{sx} is also reduced to 3.67A from 4.34A after compensation.

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

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

8.2 Dynamic response of hybrid-STATCOM:

Fig. 6 shows the dynamic performance of hybrid-STATCOM for different loadings compensation. When the load reactive power changes from capacitive to inductive, hybrid-STATCOM takes about one cycle to settle down. However, when the load reactive power is changing within the inductive range, the transient time is significantly reduced and the waveforms are smooth. Meanwhile, the fundamental reactive power is compensated to around zero even during the transient time. In practical situations, the load reactive power seldom suddenly changes from capacitive to inductive or vice versa, and thus hybrid-STATCOM can obtain good dynamic performance

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.*

According to the above simulation results, Table II verifies the V-I characteristics of the traditional STATCOM, C-STATCOM, and hybrid-STATCOM, as shown in Fig. 2. With similar compensation performance, the capacity of the active inverter part (or DC-link voltage) of the proposed hybrid-STATCOM is only about 16% of that of traditional STATCOM under wide range compensation (both inductive and capacitive). According to the cost study in [14] and [17], the average cost of traditional STATCOM is around USD $60/kVA, whereas that of SVC is only approximately $23/kVA. Therefore, by rough calculation, the average cost of the proposed hybrid-STATCOM is just about $33/kVA (=$60/kVA*16% +$23/kVA), which is 55% of the average cost of traditional STATCOM. Moreover, because the proposed hybrid-STATCOM can avoid the use of multilevel structures in medium-voltage level transmission system in comparison to traditional STATCOM, the system reliability can be highly increased and the system control complexity and operational costs can be greatly reduced.

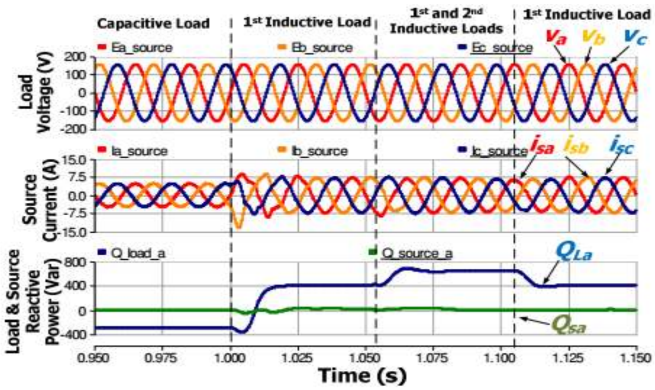
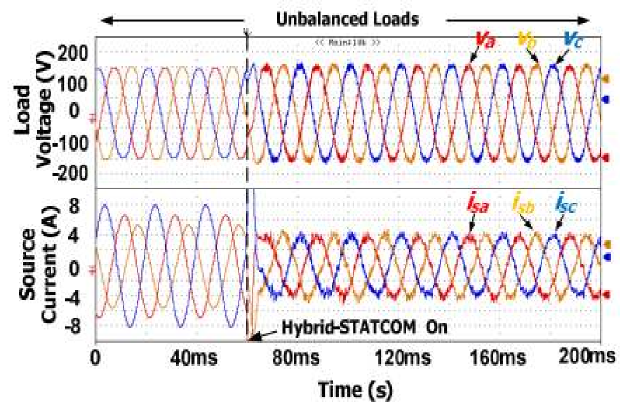


Fig: 6. Dynamic compensation waveforms of load voltage, source current, and load and source reactive powers by applying hybrid-STATCOM under different loadings cases.

Based on the above simulation results, a summary can be drawn as follows:

- The traditional STATCOM can compensate for both inductive and capacitive reactive currents with a high DC-link operating voltage due to a small coupling inductor.
- Due to its high DC-link voltage, the traditional STATCOM obtains the poor source current THD_{isx} (caused by switching noise) compared with hybrid-STATCOM.
- C-STATCOM has a low DC-link voltage characteristic only under a narrow inductive loading range. However, when the loading current is outside its designed range, the C-STATCOM requires a very high DC-link operating voltage due to a large coupling capacitor.
- The hybrid-STATCOM obtains the best performances of the three STATCOMs under both inductive and capacitive loadings.
- The hybrid-STATCOM has a wide compensation range with low DC-link voltage characteristic and good dynamic performance.



Conclusions:

In this paper, a hybrid-STATCOM in three-phase power system is proposed and discussed as a cost-effective reactive power compensator for medium voltage level application. The system configuration and V-I characteristic of the hybrid-STATCOM are analyzed, discussed, and compared with traditional STATCOM and C-STATCOM. In addition, its parameter design method is proposed on the basis of consideration of the reactive power compensation range and prevention of a potential resonance problem. Moreover, the control strategy of the hybrid-STATCOM is developed under different voltage and current conditions. Finally, the wide compensation range and low DC-link voltage characteristics with good dynamic performance of the hybrid-STATCOM are proved by both simulation and experimental results.

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