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Reactive Power Compensation by using (Hybrid-STATCOM) with Wide Compensation Rage

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Abstract: The STATCOM(STATicSynchronousCOMpensator) is a shunt connected voltage source converter using self-commutating device and can be explicitly used for reactive power control. Its principle of operation is similar to that of a synchronous condenser. This paper describes the modeling of STATCOM along with the design of linear current and voltage controllers. The design of controllers for the converters can be realized in two ways. The first procedure is a non-linear realization, which results in simple control rules with faster dynamics. The second procedure is a linear method, which requires system modeling. The first approach is adopted and simulated waveforms are presented in the paper. The designed controllers with variation of DC link voltage have been applied to the STATCOM and suitable DC link voltage has been selected on basis of spike and over shoot of the responses. All responses are obtained through MATLAB SIMULINK tool box and presented here for clarity of the control strategy.

Keywords: Hybrid-STATCOM, Capacitive-Coupled Static Synchronous Compensator (C-STATCOM), Low DC-Link Voltage, STATCOM, Wide Compensation Range.

I. INTRODUCTION

The Modern power distribution system is becoming highly vulnerable to the different power quality problems. The extensive use of nonlinear loads is further contributing to increased current and voltage harmonics issues. Furthermore, the penetration level of small/large-scale renewable energy systems based on wind energy, solar energy, fuel cell, etc., installed at distribution as well as transmission levels is increasing significantly. This integration of renewable energy sources in a power system is further imposing new challenges to the electrical power industry to accommodate these newly emerging distributed generation systems. To maintain the controlled power quality regulations, some kind of compensation at all the power levels is becoming a common practice. At the distribution level, Statcom is a most attractive solution to compensate several major power quality problems. Reactive power compensation is an important issue in the control of distribution systems. Reactive current increases the distribution system losses, reduces the system power factor, shrink the active power capability and can cause large-amplitude variations in the load-side voltage. Various methods have been applied to mitigate voltage sags. The conventional methods use capacitor banks, new parallel feeders, and uninterruptible power supplies (UPS). However, the power quality problems are not completely solved due to uncontrollable reactive power compensation and high costs of new feeders and UPS. The STATCOM has emerged as a promising device to provide not only for voltage sag mitigation but also for a host of other power quality solutions such as voltage stabilization, flicker suppression, power factor correction, and harmonic control.

STATCOM is a shunt device that generates a balanced three-phase voltage or current with ability to control the magnitude and the phase angle. 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-basedcontrol[13],instantaneoussymmetrical 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 structure. In addition, these two parallel connected-hybrid-STATCOM structures [15]–[17] may suffer from a resonance problem.

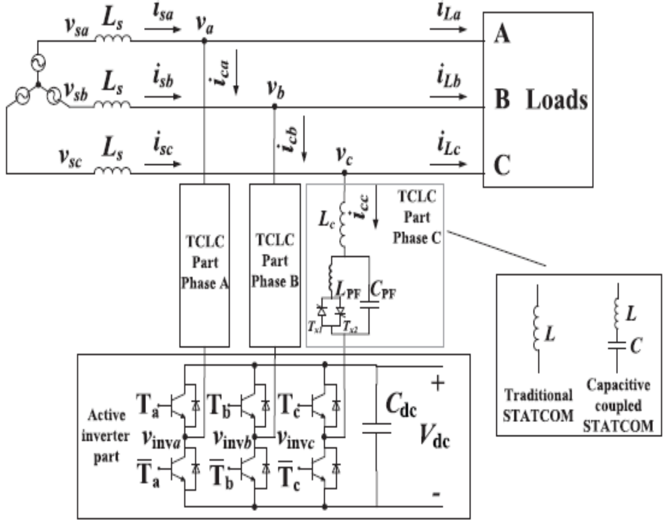


Fig. 1. Circuit configuration of the hybrid-STATCOM.

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 (TCLC) part and an active inverter part, as shown in Fig1. 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. 1) A hybrid-STATCOM is proposed, with the distinctive characteristics of a much wider compensation range than C-STATCOM [10] and other series-type PPFSTATCOMs [11]–[19] and a much lower dc-link voltage than traditional STATCOM [4]–[9] and other parallelconnected hybrid-STATCOMs [20]–[22]. 2) 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. 3) 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. 4) 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. 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 dclink voltage characteristics and the dynamic performance of the proposed hybrid-STATCOM.

II. CIRCUIT CONFIGURATION OF THE HYBRID-STATCOM

Fig1 shows the circuit configuration of hybrid-STATCOM, in which the subscript x stands for phase a, b, and c in the following analysis. v_{sx} and v_x are the source and load voltages; i_{sx}, i_{Lx}, and i_{cx} are the source, load, and compensating currents, respectively. Ls is the transmission line impedance. The hybrid-STATCOM consists of a TCLC and an active inverter part. The TCLC part is composed of a coupling inductor Lc, a parallel capacitor CPF, and a thyristor-controlled reactor with LPF. The TCLC part provides a wide and continuous inductive and capacitive reactive power compensation range that is controlled by controlling the firing angles αx of the thyristors. The active inverter part is composed of a voltage source inverter with a dc-link capacitor Cdc, and the small rating active inverter part is used to improve the performance of the TCLC part. In addition, the coupling components of the traditional STATCOM and C-STATCOM are also presented in Fig. 1.

V. 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. 2.

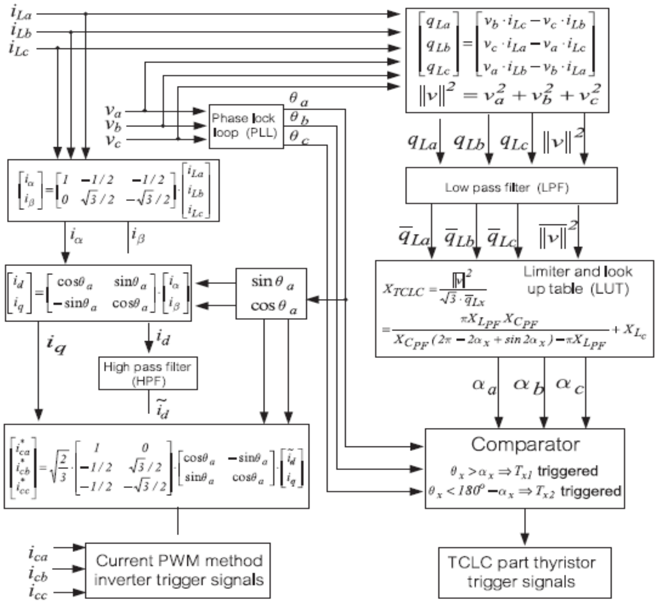


Fig. 2. Control block diagram of hybrid-STATCOM.

A. 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 XTCLC. Referring to (3), to obtain the minimum inverter voltage Vinvx ≈ 0, XTCLC can be calculated with Ohm's law in terms of the RMS values of the load voltage (Vx) and the load reactive current (ILqx). However, to calculate the XTCLC in real time, the expression of XTCLC can be rewritten in terms of instantaneous values as

$$X_{\mathrm{TCLC}} = \frac{V_x}{I_{Lqx}} = \frac{\overline{\|v\|}^2}{\sqrt{3}\cdot \bar{q}_{Lx}} \qquad (1)$$

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

$$\begin{bmatrix} q_{La} \\ q_{Lb} \\ q_{Lc} \end{bmatrix} = \begin{bmatrix} v_b \cdot i_{Lc} - v_c \cdot i_{Lb} \\ v_c \cdot i_{La} - v_a \cdot i_{Lc} \\ v_a \cdot i_{Lb} - v_b \cdot i_{La} \end{bmatrix}. \qquad (3)$$

In (21) and (22), v_x and q_{Lx} are the instantaneous load voltage and the load reactive power, respectively. As shown in Fig2, a limiter is applied to limit the calculated XTCLC in (9) within the range of XTCLC > Xind(min) and XTCLC < XCap(min) (XCap(min) < 0). With the calculated XTCLC, the firing angle αx 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 αx with θx, which is the phase angle of the load voltage vx. θx 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.

B. Active Inverter Part Control

In the proposed control strategy, the instantaneous active and reactive current id–iq 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 icx 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 id–iq 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 icx 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

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_a & -\sin\theta_a \\ \sin\theta_a & \cos\theta_a \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_d \\ i_q \end{bmatrix} \qquad (4)$$

where id and iq are the instantaneous active and reactive current, which include dc components¯id and¯iq, and ac components ˜I d and˜iq.˜id is obtained by passing id through a high-pass filter. id and iq are obtained by

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta_a & \sin\theta_a \\ -\sin\theta_a & \cos\theta_a \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \qquad (5)$$

In (24), the currents (iα and iβ) in α–β plane are transformed from a–b–c frames by

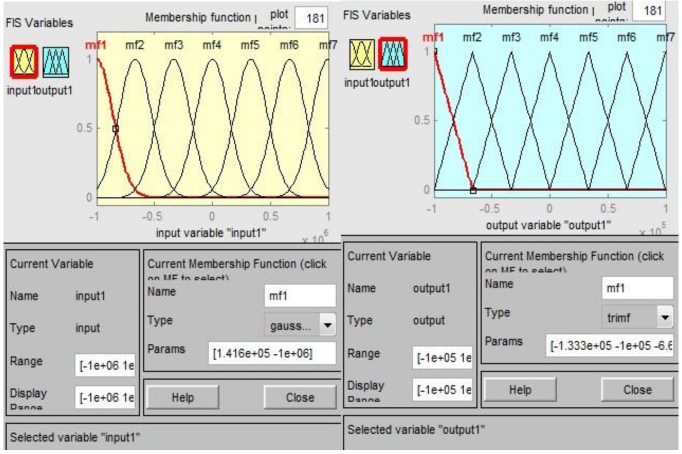
$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (6)$$

where i_{Lx} is the load current signal.

C. 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 (0.02s). 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 icx 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. 1) 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. 2) 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 2 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 (Fig4). In this paper we introduce a fuzzy logic controller in place of PI controller of V_{dc} error generator. The fuzzy controller used in this current reference generator has „7" input membership functions and seven ouput membership function. The membership functions can be seen below in fig3.



Plot points: 181

Current Variable
Name input1
Type input
Range [-1e+06 1e
Display Range [-1e+06 1e

Current Membership Function (click on MF to select)
Name mf1
Type gauss...
Params [1.416e+05 -1e+06]

Selected variable "input1"

Plot points: 181

Current Variable
Name output1
Type output
Range [-1e+05 1e
Display Range [-1e+05 1e

Current Membership Function (click on MF to select)
Name mf1
Type trimf
Params [-1.333e+05 -1e+05 -6.6

Selected variable "output1"

Fig3. Fuzzy input and output membership functions.

VI. 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 Vdc =√2 ·√3 · Vinvx) for these three STATCOMs are also verified by simulations. The simulation studies are carried out with MATLAB. When the loading is inductive and light, traditional STATCOM requires a high dc-link voltage (Vdc >√2 ·VL–L=269V, Vdc=300V) for compensation. After compensation, the source current isx is reduced to 5.55 A from 6.50 A, and the source-side displacement power factor (DPF) becomes unity from 0.83. In addition, the source current total harmonics distortion (THDisx) is 7.22% after compensation, which satisfies the international standard [24] (THDisx < 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 (Vdc = 80 V). The isx,DPF, and THDisx are compensated to 5.48 A, unity, and 2.01%, respectively. For the proposed hybrid-STATCOM, the isx, DPF, and THDisx are compensated to 5.48 A, unity, and 1.98%, respectively. As discussed in the previous section, a low dc-link voltage (Vdc = 50 V) of hybrid-STATCOM is used to avoid mistuning of firing angles, prevent resonance problems, and reduce the injected harmonic currents. To compensate for the inductive and heavy loading, traditional STATCOM still requires a high dc-link voltage of Vdc = 300V for compensation. Traditional STATCOM can obtain acceptable results (DPF = 1.00 and THDisx = 6.55%). The isx is reduced to 5.95 A from 8.40 A after compensation. With a low dc-link voltage (Vdc = 50 V), C-STATCOM cannot provide satisfactory compensation results (DPF = 0.85 and THDisx = 17.5%). However, when the dc-link voltage is increased to Vdc = 300 V, the compensation results (DPF = 1.00 and THDisx = 7.02%) are acceptable and satisfy the international standard [24] (THDisx < 15%). The isx is reduced to 5.90 A from 8.40 A 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 Vdc = 50 V. The isx is reduced to 5.89 A from 8.40 A after compensation.

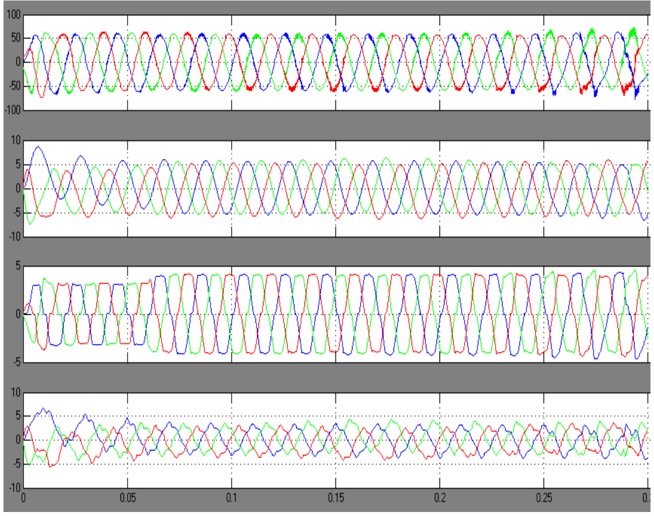


Fig4.Dynamic compensation waveforms of source voltage, source current, and load current and compensating currents by applying hybrid-STATCOM.

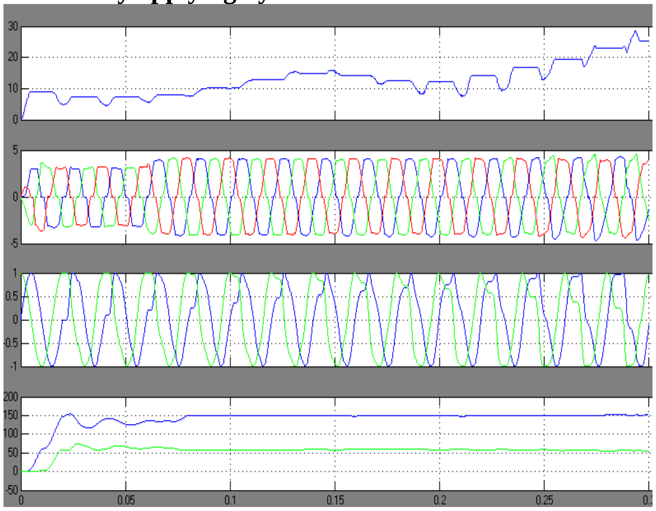


Fig5.Dynamic compensation waveforms of dc bus voltage, load current sin cos angles and source active and reactive powers by applying hybrid-STATCOM.

V. CONCLUSION

The complete analysis and models of reactive current and voltage controllers of the STATCOM application are presented. The controllers are designed on the basis of parameters of the STATCOM and time constant. The simulated figures with designed controllers and on variation of DC link voltages are given which have been controlled the desired values. The settling time of the system by using the Fuzzy controller is faster than other controllers. On increasing the magnitude of DC link voltage, the overshoot of all signals decreases. DC link voltage at 600V is suitable for proper operation of the STATCOM. In most cases, there is a separate charging circuit for the DC link voltage. The authors are working on a plausible method of eliminating such an extra starting arrangement, so that the controller may become operational while the DC link voltage is at a low value.

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