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FIVE LEVEL INVERTER WITH HYBRID STATCOM FOR WIDE COMPENSATION RANGE WITH LOW DC LINK VOLTAGE

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Abstract-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. 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. A five-level diode clamped multilevel inverter is developed and applied for injecting the real power into the grid. Its V-I characteristic is then analyzed, discussed, and compared with traditional STATCOM and capacitive-coupled STATCOM (C-STATCOM). The system parameter design is proposed on the basis of consideration of the reactive power compensation range and avoidance of the potential resonance problem. A novel control strategy for hybrid-STATCOM is adopted to mitigate the power quality issues such as unbalanced current, voltage dip, and voltage fault. Simulation results shows the wide compensation range and low DC-link voltage characteristics and the good dynamic performance of the proposed hybrid-STATCOM.

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

I. INTRODUCTION

A hybrid-STATCOM is proposed, with the distinctive characteristics of a much wider compensation range than C-STATCOM [10] and other series-type PPF-STATCOMs and a much lower DC-link voltage than traditional STATCOM [4]-[9] and other parallel-connected hybrid STATCOMs. To improve the operating performances of the traditional STATCOMs, C-STATCOMs, and other PPF-STATCOMs, many different control techniques have been proposed.

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]. 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]. 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].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.

To reduce the current rating of the STATCOMs or APFs, a hybrid combination structure of PPF in parallel with STATCOM was proposed. 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 overcome the shortcomings of different reactive power compensators [1]-[10] 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.

II. CIRCUIT CONFIGURATION OF THE HYBRID-STATCOM

Fig. 1 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,

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respectively. L_s 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 L_c, a parallel capacitor C_{PF}, and a thyristor-controlled reactor with L_{PF}. The TCLC part provides a wide and continuous inductive and capacitive reactive power compensation range that is controlled by controlling the firing angles α_x of the thyristors.

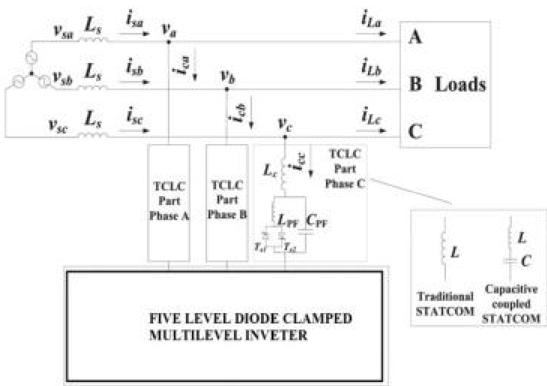

Fig. 1. Circuit configuration of the hybrid-STATCOM.

The active inverter part is composed of a voltage source inverter with a DC-link capacitor C_{dc}, 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.

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

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 (Q_{Lx}) consumed, but with the opposite polarity (Q_{cx}=-Q_{Lx}). The hybrid-STATCOM compensating reactive power Q_{cx} is the sum of the reactive power Q_{TCLC} that is provided by the TCLC part and the reactive power Q_{invx} that is provided by the active inverter part. Therefore, the relationship among Q_{Lx}, Q_{TCLC}, and Q_{invx} can be expressed as

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

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

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

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

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

where the TCLC part impedance $X_{TCLC(\alpha x)}$ can be expressed as

$$X_{TCLC}(\alpha_x) = \frac{X_{TCR}(\alpha_x) X_{C_{pf}}}{X_{C_{pf}} - X_{TCR}(\alpha_x)} + X_{Lc} = \frac{\pi X_{L_{pf}} X_{C_{pf}}}{X_{C_{pf}}(2\pi - 2\alpha_x + \sin 2\alpha_x) - \pi X_{L_{pf}}} + X_{Lc} \quad (4)$$

where X_{Lc} , X_{LPF} , and X_{CPF} are the fundamental impedances of L_c, L_{PF}, and C_{PF}, 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=90^o and α_x=180^o, respectively. In the following discussion, the minimum value for impedances stands for its absolute value. The minimum inductive ($X_{ind(min)}$>0) and capacitive ($X_{Cap(min)}$<0) TCLC part impedances can be expressed as

$$X_{Ind(min)}(\alpha_x = 90^0) = \frac{X_{L_{PF}} X_{C_{PF}}}{X_{C_{PF}} - X_{L_{PF}}} + X_{L_c} \quad (5)$$

$$X_{Cap(min)}(\alpha_x = 180^0) = -X_{C_{PF}} + X_{L_c} \quad (6)$$

Ideally, $X_{TCLC(\alpha x)}$ is controlled to be Vx ≈ $X_{TCLC}(\alpha_x) I_{Lqx}$, so that the minimum inverter voltage (V_{invx} ≈ 0V) can be obtained as shown in (3). In this case, the switching loss and switching noise can be significantly reduced. A small inverter voltage $V_{invx(min)}$ 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

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the loading capacitive current or inductive current is outside the TCLC part compensating range, the inverter voltage V_{invx} will be slightly increased to further enlarge the compensation range. Christo Ananth et al.[3] presented a brief outline on Electronic Devices and Circuits which forms the basis of the Clampers and Diodes.

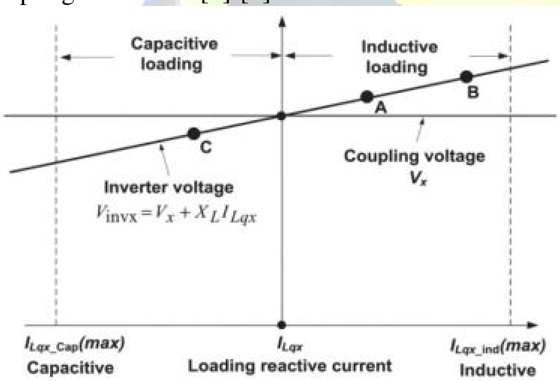
The coupling impedances for traditional STATCOM and C-STATCOM, as shown in Fig. 1, are fixed as X_L and X_C-1/X_L. The relationships among the load voltage V_x, the inverter voltage V_{invx}, the load reactive current I_{Lqx}, and the coupling impedance of traditional STATCOM and C-STATCOM can be expressed as

$$V_{invx} = V_x + X_L I_{Lqx} \quad (7)$$

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

where $X_L >> X_C$. 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 traditional STATCOM as shown in Fig. 2(a), the required V_{invx} is larger than V_x when the loading is inductive. In contrast, the required V_{invx} is smaller than V_x when the loading is capacitive. Actually, the required inverter voltage V_{invx} is close to the coupling voltage V_x, due to the small value of coupling inductor L [5]-[8].



(a)

Fig. 2. V-I characteristic of (a) traditional STATCOM,

For C-STATCOM as shown in Fig. 2(b), it is shown that the required V_{invx} is lower than V_x under a small inductive loading range.

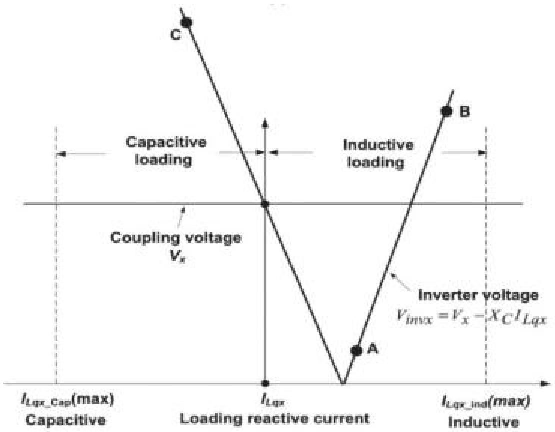
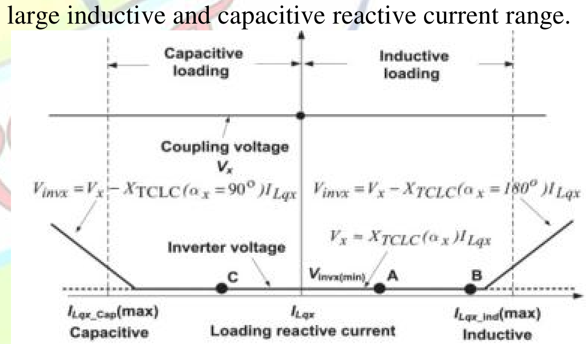


Fig. 2. V-I characteristic of, (b) C-STATCOM.

The required V_{invx} can be as low as zero when the coupling capacitor can fully compensate for the loading reactive current. In contrast, V_{invx} is larger than V_x when the loading is capacitive or outside its small inductive loading range. Therefore, when the loading reactive current is outside its designed inductive range, the required V_{invx} can be very large.

For the proposed hybrid-STATCOM as shown in Fig. 2(c), the required V_{invx} can be maintained at a low (minimum) level ($V_{invx(min)}$) for a large inductive and capacitive reactive current range.



(c)

Fig. 2. V-I characteristic of (c) hybrid-STATCOM

Moreover, when the loading reactive current is outside the compensation range of the TCLC part, the V_{invx} will be slightly increased to further enlarge the compensating range.

IV. 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.

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A. 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.

$$Q_{cx(MaxCap)} = \frac{V_x^2}{X_{Cap(min)}(\alpha_x=180^0)} = -\frac{V_x^2}{X_{C_{PF}}-X_{L_C}} \quad (10)$$

$$Q_{cx(MaxInd)} = \frac{V_x^2}{X_{Ind(min)}(\alpha_x=90^0)} = -\frac{V_x^2}{\frac{X_{C_{PF}}X_{L_{PF}}}{X_{C_{PF}}-X_{L_{PF}}}+X_{L_C}} \quad (11)$$

where the minimum inductive impendence $X_{Ind(min)}$ and the capacitive impendence $X_{Cap(min)}$ are obtained from (5) and (6), respectively.

B. Design of Lc

For exciting resonance problems, a sufficient level of harmonic source voltages or currents must be present at or near the resonant frequency.

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. The simplified single-phase equivalent circuit model of hybrid-STATCOM is shown in Fig. 3.

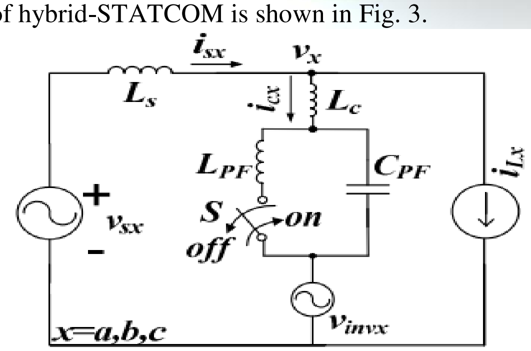

Fig. 3. Simplified single-phase equivalent circuit model of hybrid-STATCOM.

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. 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

$$X_{LC,n}(n) = \left|\frac{1-(n\omega)^2 L_C C_{PF}}{n\omega C_{PF}}\right| \quad (12)$$

$$X_{LC,n}(n) = \left|\frac{n\omega(L_C+L_{PF})-(n\omega)^3 L_{PF} L_C C_{PF}}{1-(n\omega)^2 L_{PF} C_{PF}}\right| \quad (13)$$

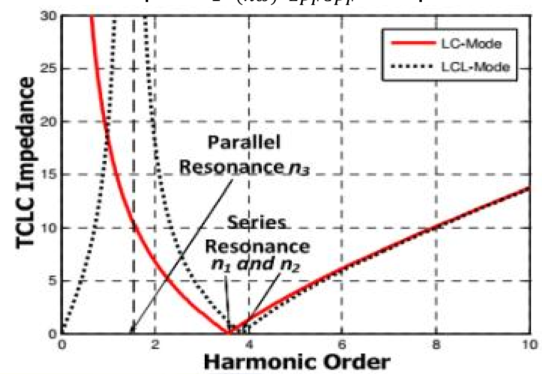

Fig. 4. TCLC impedance under different harmonic order.

C. 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

$$V_{incx} = V_x\left[1+\frac{V_x I_{Lqx}}{V_x^2/X_{TCLC}(\alpha_x)}\right] = V_x\left[1+\frac{Q_{Lx}}{Q_{cx,TCLC}(\alpha_x)}\right] \quad (14)$$

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.

V. CONTROL STRATEGY OF HYBRID-STATCOM

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. 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.

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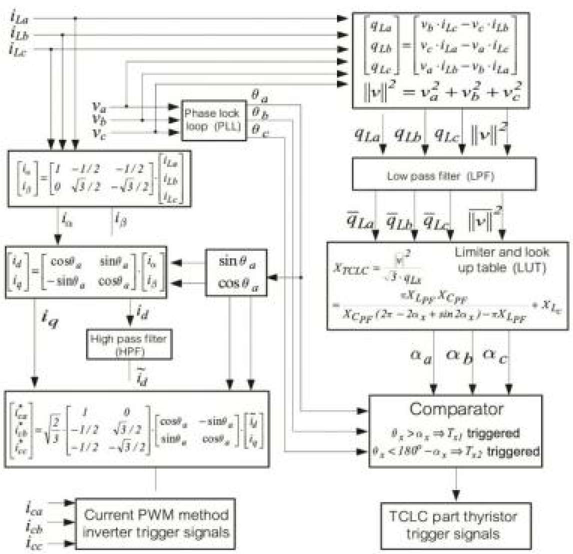

Fig. 5. The control block diagram of hybrid-STATCOM.

A. TCLC part control

Different with the traditional SVC control based on the traditional definition of reactive power [2], 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 $V_{invx} \approx 0V$, 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 X_{TCLC} can be rewritten in terms of instantaneous values as

$$X_{TCLC} = \frac{V_x}{I_{Lqx}} = \frac{\|\bar{v}^2\|}{\sqrt{3}.\bar{q}_{Lx}} \quad (15)$$

where v is the norm of the three-phase instantaneous load voltage and q_{Lx} is the DC component of the phase reactive power.

B. Active inverter part control

In the proposed control strategy, the instantaneous active and reactive current i_d-i_q method [7] is implemented.

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

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc}\end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2\end{bmatrix}\cdot\begin{bmatrix}\cos\theta_a & -\sin\theta_a \\ \sin\theta_a & \cos\theta_a\end{bmatrix}\cdot\begin{bmatrix}\tilde{i}_d \\ i_q\end{bmatrix} \quad (16)$$

where i_d and i_q are the instantaneous active and reactive current.

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 (0.02 s).

VI. MULTILEVEL INVERTER

Now a days many industrial applications have begun to require high power. Some appliances in the industries however require medium or low power for their operation. Using a high power source for all industrial loads may prove beneficial to some motors requiring high power, while it may damage the other loads. Some medium voltage motor drives and utility applications require medium voltage.

Types of Multilevel Inverter:

Multilevel inverters are three types.

- Diode clamped multilevel inverter
- Flying capacitors multilevel inverter
- Cascaded H- bridge multilevel inverter

Diode Clamped Multilevel Inverter:

The main concept of this inverter is to use diodes and provides the multiple voltage levels through the different phases to the capacitor banks which are in series. A diode transfers a limited amount of voltage, thereby reducing the stress on other electrical devices. The maximum output voltage is half of the input DC voltage. It is the main drawback of the diode clamped multilevel inverter. This problem can be solved by increasing the switches, diodes, capacitors. Due to the capacitor balancing issues, these are limited to the three levels. This type of inverters provides the high efficiency because the fundamental frequency used for all the switching devices and it is a simple method of the back to back power transfer systems.

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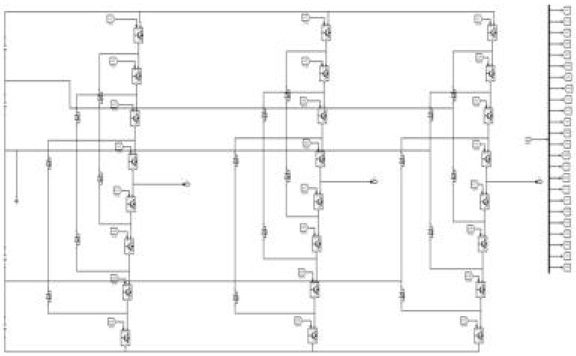


Fig. 6. 5-Level Diode Clamped Multilevel Inverter

Applications of Diode Clamped Multilevel Inverter:

- Static var compensation
- Variable speed motor drives
- High voltage system interconnections
- High voltage DC and AC transmission lines

VII. SIMULATION RESULTS

In this section, the simulation results of proposed hybrid-STATCOM with five level diode clamped multilevel inverter is discussed.

A. Inductive and light loading

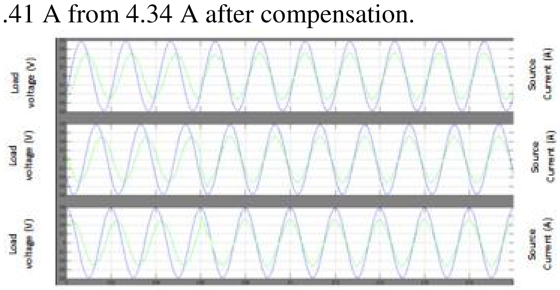
For the proposed hybrid-STATCOM, the i_{sx}, DPF, and THD_{isx} are compensated to 5.48 A, unity, and 1.98%, respectively. As discussed in the previous, a low dc-link voltage (V_{dc} = 50 V) of hybrid-STATCOM is used to avoid mistuning of firing angles, prevent resonance problems, and reduce the injected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

B. Inductive and heavy loading

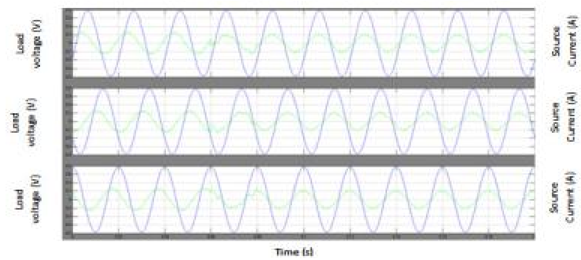
The proposed hybrid-STATCOM can still obtain acceptable compensation results (DPF = 1.00 and THD_{isx} =3 .01%) with a low dc-link voltage of V_{dc} = 50 V. The i_{sx} is reduced to 5.89 A from 8.40A after compensation.

C. Capacitive loading

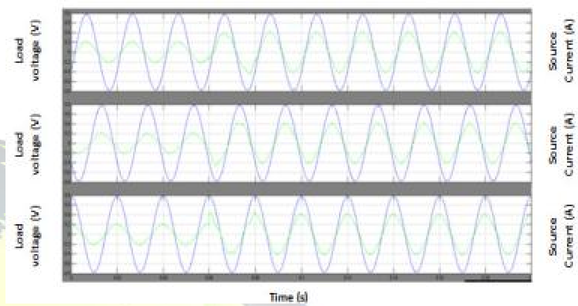
With the lowest dc-link voltage (V_{dc} = 50 V) of the three STATCOMs, hybrid-STATCOM can still obtain the best compensation results with DPF = 1.00 and THD_{isx} =3 .01%. In addition, the i_{sx} is reduced to 3.41 A from 4.34 A after compensation.



(a)



(b)



(c)

Fig. 8. Dynamic compensation waveforms of v_x and i_{sx} by applying hybrid-STATCOM under (a) inductive load; (b) capacitive load; and (c) changing from capacitive load to inductive load

D. Dynamic response of hybrid-STATCOM

Fig. 9 shows the dynamic performance of hybrid-STATCOM for different loadings compensation.

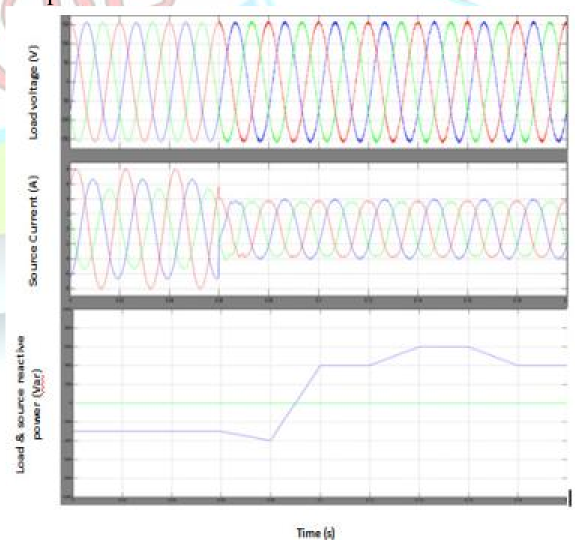


Fig. 9. Dynamic compensation waveforms of load voltage, source current, and load and source reactive powers by applying hybrid-STATCOM under different loadings cases.

Meanwhile, the fundamental reactive power is compensated to around zero even during the

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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.

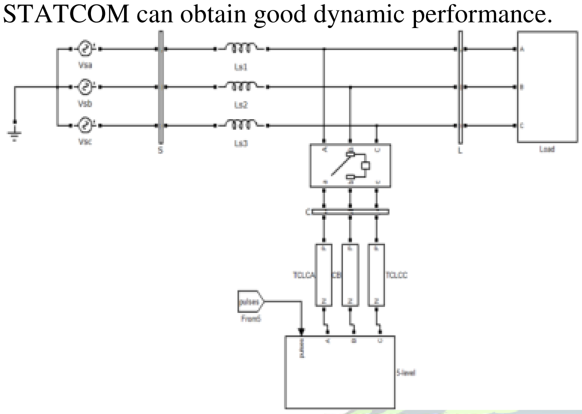

Fig. 10. Block diagram of simulation

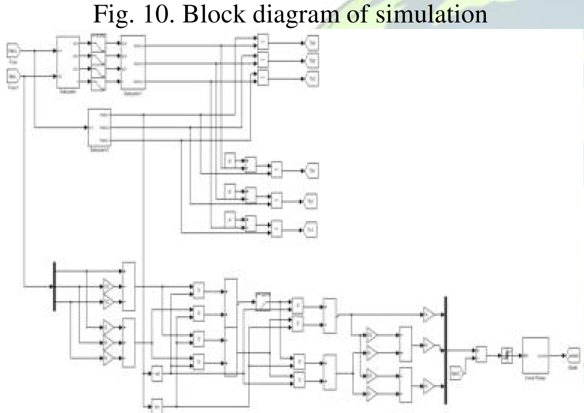

Fig. 11. Control block diagram of simulation

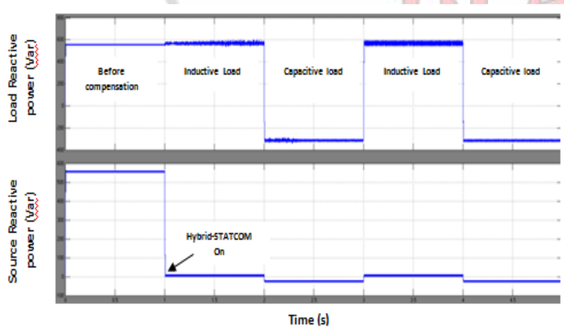

Fig. 12. Dynamic reactive power compensation of phase a by applying hybrid-STATCOM

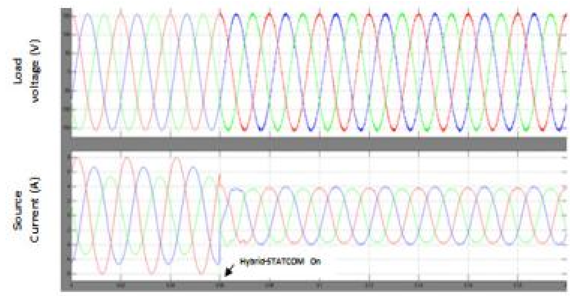

Fig. 13. Dynamic compensation waveforms of v_x and i_{sx} by applying hybrid-STATCOM under unbalanced loads

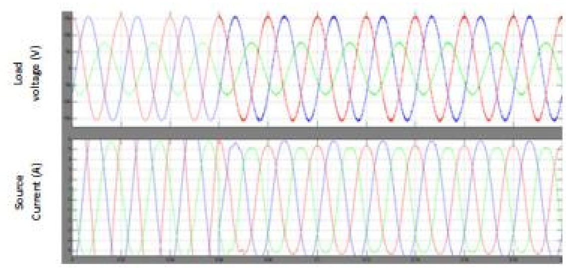

Fig. 14.Dynamic compensation waveforms of v_x and i_{sx} by applying hybrid STATCOM under voltage fault condition

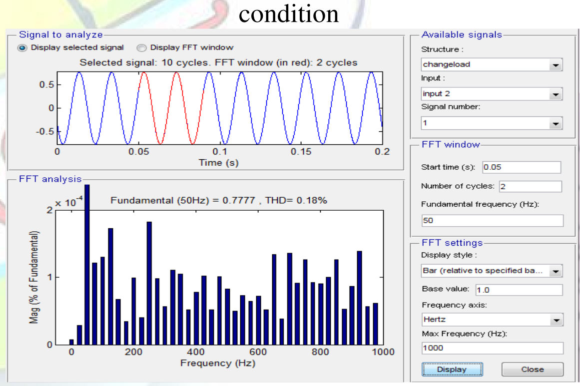

Fig. 15. THD in output current using hybrid-STATCOM

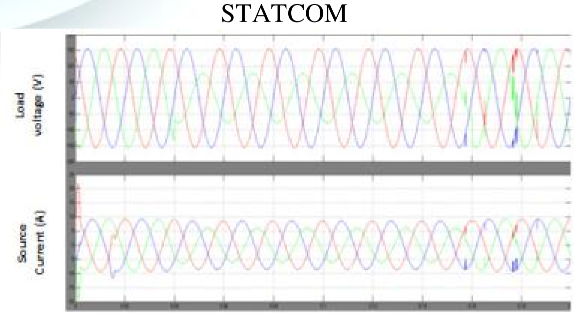

Fig. 16.Dynamic compensation waveforms of v_x and i_{sx} by applying hybrid STATCOM during voltage dip.

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IX. CONCLUSION

The circuit configuration of hybrid-STATCOM is proposed in this paper. 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 is proposed in this paper**.** Compared with traditional STATCOM and C-STATCOM the system configuration and V-I characteristic of the hybrid-STATCOM are analyzed in this paper. 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. By using five-level inverter is developed and applied for injecting the real power of the renewable power into the grid to reduce the switching power loss, harmonic distortion, and electromagnetic interference caused by the switching operation of power electronic devices.By using the simulation results we can analyze the wide compensation range and low DC-link voltage characteristics with good dynamic performance of the hybrid-STATCOM.

TABLE II
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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