Investigation of A Novel Capacitive-Coupled STATCOM: Modeling and Simulation

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Abstract-**In this paper, a novel capacitive-coupled STATCOM in three-phase power system is proposed, which can lower the rating of the conventional inductive-coupled STATCOM. Thus, this feature benefits by reducing the system initial cost, switching loss and electromagnetic interference (EMI) problems. The modeling, V-I characteristic of the capacitive-coupled STATCOM is proposed and investigated compared with the inductive-coupled case. Finally, simulation results are given to verify the viability and effectiveness of the proposed novel STATCOM and its compensation characteristic.**

I. INTRODUCTION

In modern power transmission system, the steady-state transmittable power can be increased and the voltage profile along the line controlled by appropriate reactive compensation. The purpose of this reactive compensation is to change the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand. Traditionally, reactive power problem has usually been compensated with Static VAR Compensator (SVC). However, if higher system dynamic performance, wider operation range and less harmonic current generation are required, STATCOM (Static Synchronous Compensator) should be applied [1] – [4]. Compared with SVC, STATCOM has significant advantage of lower losses, faster response, better system stability, etc., however, the control is more complicated and the initial cost is higher.

In this paper, a novel capacitive-coupled STATCOM in three-phase power system is proposed, which can lower the dc-link rating of the conventional inductive-coupled case. This feature can reduce the system initial cost, switching loss and electromagnetic interference (EMI) problems. In addition, the modeling, V-I characteristic of the capacitive-coupled STATCOM is investigated and studied compared with that of the inductive-coupled case. Finally, simulation results are given to verify the modeling, dc-link voltage reduction and V-I characteristic of the proposed STATCOM.

II. COMPARATIVE STUDY OF CONVENTIONAL INDUCTIVE-COUPLED AND PROPOSED NOVEL CAPACITIVE-COUPLED STATCOMs

A. *Theoretical Analysis of the Conventional Inductive-coupled and Proposed Novel Capacitive-coupled STATCOMs*

A conventional inductive-coupled STATCOM configuration [1], [4] is shown in Fig. 1a. Figs. 2a and 3a show its single phase equivalent model and phasor diagram. V_s , V_{inv} , I_q , I_{Lq} and X_L represent the power system RMS voltage, inverter output voltage, inject reactive current, load reactive current and coupling inductor reactance. From Fig. 2a, its V_{inv} should be larger than V_s . When the coupling component is replaced by a capacitor reactance X_C , as in Fig. 1b, its single phase equivalent model and phasor diagram are shown in Figs. 2b and 3b. From Fig. 2b, the STATCOM can do compensation even V_{inv} is smaller than V_s . Since V_{inv} value depends on the dc-link voltage (V_{dc}) level, if X_C is chosen appropriately, V_{dc} can be reduced significantly.

In ideal inductive load reactive power compensation, from Fig. 3a, the inductive-coupled case can be expressed:

$$Q_{inv} = -Q_{ind\_load} + Q_{coup\_ind} \tag{1}$$

$$V_{inv} I_q = -V_s I_{Lq} + I_q^2 X_L \tag{2}$$

,where Q_{inv} , Q_{ind_load} and Q_{coup_ind} represent the inject reactive power, reactive power drawn by inductive load, reactive power caused by X_L and $I_q = -I_{Lq}$ because they are 180° difference. If I_{Lq} is inductive, I_q should be capacitive and vice-versa. Simplify (2) yields:

$$V_{inv} = V_s + I_q X_L \tag{3}$$

From Fig. 3b, the capacitive-coupled case can be expressed:

$$Q_{inv} = -Q_{ind\_load} - Q_{coup\_cap} \tag{4}$$

$$V_{inv} I_q = -V_s I_{Lq} - I_q^2 X_c \tag{5}$$

,where Q_{coup_cap} represent the reactive power caused by X_C . Similarly, simplify (5) yields:

$$V_{inv} = V_s - I_q X_c \tag{6}$$

Compared (3) with (6), V_{inv} should be larger than V_s for the inductive-coupled case, while V_{inv} can be smaller than V_s for the capacitive-coupled case. This phenomenon implies a rating reduction potential in the proposed capacitive-coupled STATCOM. Similarly, for capacitive loading, the conventional inductive-coupled and proposed capacitive-coupled STATCOM can be predicted to have inverse phenomena as that of the inductive loading.

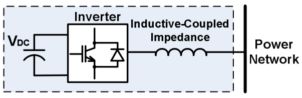

Fig. 1a Configuration of an inductive-coupled STATCOM

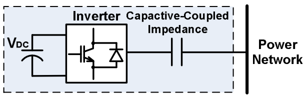

Fig. 1b Configuration of a proposed capacitive-coupled STATCOM

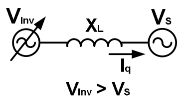

Fig. 2a Single-phase equivalent model of the inductive-coupled STATCOM at inductive load

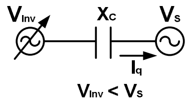

Fig. 2b Single-phase equivalent model of the capacitive-coupled STATCOM at inductive load

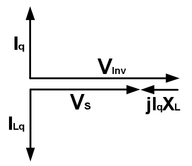

Fig. 3a Phasor diagram of the lossless inductive-coupled STATCOM at inductive load

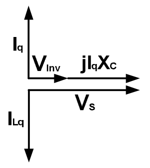

Fig. 3b Phasor diagram of the lossless capacitive-coupled STATCOM at inductive load

B. Practical Structure of the Proposed Novel Capacitive-coupled STATCOM

Since the inverter cannot yield a pure sinusoidal voltage without harmonic contents due to the high switching frequency, a small inductor (L_c) is usually added to the coupling capacitor (C_c). L_c can smooth the inverter output current waveform, and also prevent a large inrush current ($C_c dv/dt$) happens, but $X_C >> X_L$ at fundamental frequency. Also, L_c can be made used for the capacitive load compensation, even capacitive loading is not common. Figs. 1b-3b are modified into Figs. 4-6 for practical operation. And V_{inv} under inductive and capacitive load can be expressed as:

$$V_{invi} = V_{si} + I_{qi}\left(\omega L_c - \frac{1}{\omega C_c}\right),\ i=a,b,c \tag{7}$$

$$V_{invi} = V_{si} - I_{qi}\omega L_c,\ i=a,b,c \tag{8}$$

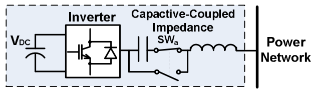

Fig. 4a Configuration of the capacitive-coupled STATCOM at inductive load

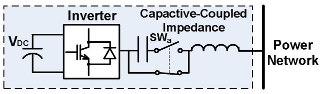

Fig. 4b Configuration of the capacitive-coupled STATCOM at capacitive load

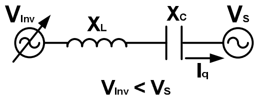

Fig. 5a Single-phase equivalent model of the capacitive-coupled STATCOM at inductive load

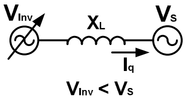

Fig. 5b Single-phase equivalent model of the capacitive-coupled STATCOM at capacitive load

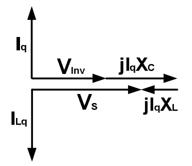

Fig. 6a Phasor diagram of the lossless capacitive-coupled STATCOM at inductive load

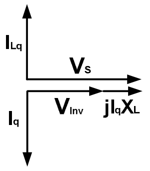

Fig. 6b Phasor diagram of the lossless capacitive-coupled STATCOM at capacitive load

C. V-I Characteristic of the Conventional Inductive-coupled and Proposed Novel Capacitive-coupled STATCOMs

Fig. 7 shows the controlled V-I characteristic of the conventional inductive-coupled STATCOM [1], [5] and the proposed novel capacitive-coupled STATCOM. Since the equivalent reactance (X_{eq}) is set, V_{inv} can be changed either raising or decreasing it towards $V_{inv(Max)}$ or $V_{inv(Min)}$ to obtain the inject capacitive or inductive reactive current (I_q). Provided V_s is within the allowable voltage variation range ($V_s + \Delta V$ or $V_s - \Delta V$), the STATCOM can maintain I_q by varying V_{inv} correspondingly.

From Fig. 7a, when the inductive-coupled STATCOM is working under capacitive loading, the required V_{inv} can be smaller than V_s. Moreover, the larger the I_q, the smaller the V_{inv} required and vice-versa. The largest V_{inv} required happens during no compensation ($I_q = 0$, $V_{inv} = V_s$). Inversely, the situation is opposite under inductive loading. The required V_{inv} should be larger than V_s. The larger the I_q, the larger V_{inv} required. The largest V_{inv} required happens during full load compensation ($I_q = -I_{Lq(rated)}$, $V_{inv} > V_s$). The X_L value is also inversely proportional to V_{inv} required.

Fig. 7b shows a V-shape V-I characteristic of the proposed capacitive-coupled STATCOM. When it is working under inductive loading, the required V_{inv} can be smaller than V_s. Moreover, the larger the I_q, the smaller the V_{inv} required and vice-versa. As the slope X_c is much larger than X_L, the required V_{inv} can be small at $I_{Lq(rated)}$. In contrast, the largest V_{inv} required happens during no compensation ($I_q = 0$, $V_{inv} = V_s$). If X_c can be bypass for capacitive load compensation, as shown in Fig. 4b, it also has the same phenomenon as that of the inductive-coupled case. Therefore, the proposed STATCOM can have a lower dc-link voltage requirement, which is superior to the inductive-coupled STATCOM. If $X_{eq} = X_C = 2X_L$, the V-shape V-I characteristic will be symmetric as shown in Fig. 7c.

Fig. 7a and b, the voltage support of the inductive-coupled STATCOM is better under inductive loading. And the voltage support capability also depends on the coupling component. The regions between the transient rated current and the steady-state rated current indicated that I_q can be temporary over its steady-state rated value as well during transient-state. The over steady-state rated current and its duration are determined by the IGBT heat-sink heat capacity and the IGBT maximum short circuit current.

From Figs. 7a and b, the $V_{inv(Max)}$ required for the conventional inductive-coupled and proposed capacitive-coupled cases are:

$$V_{inv(Max)} = V_s + \Delta V + I_{q(rated)} X_L \tag{9}$$

$$V_{inv(Max)} = V_s + \Delta V \tag{10}$$

Thus, the minimum dc-link voltage required for both STATCOMs in three-phase system can be designed as:

$$V_{dc(min)} = \sqrt{2} \cdot \sqrt{3} V_{inv(Max)} \tag{11}$$

Since (9) is always greater than (10), the minimum dc-link voltage required for the proposed STATCOM will be smaller.

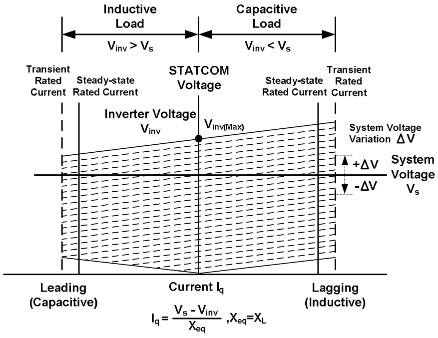

Fig. 7a Controlled V-I characteristic of the conventional inductive-coupled STATCOM

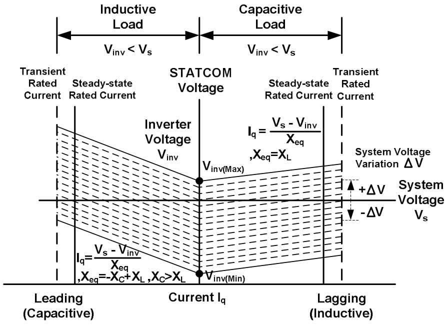

Fig. 7b Controlled V-I characteristic of the proposed capacitive-coupled STATCOM

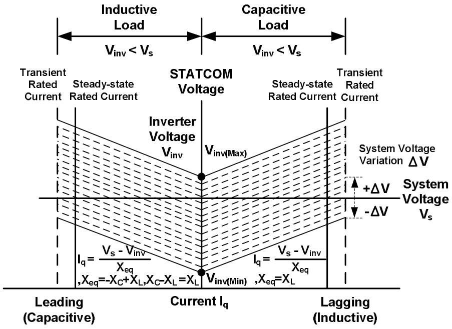

Fig. 7c Controlled V-I characteristic of the proposed capacitive-coupled STATCOM ($X_{eq} = X_C = 2X_L$)

D. *Determination of Coupling Capacitance and Inductance*

For both STATCOMs, L_c can be chosen by (12), where E is the V_{inv} difference between two voltage level (E depends on V_{dc} magnitude), T_S is the period of PWM, ΔI is the output current ripple fluctuant range, k is a scale factor. Since V_{inv} will not maintain at a same voltage level state in whole T_S, the practical L_c is usually smaller and chosen by (12), thus k is usually chosen between 0.4 ~ 0.6. Moreover, X_c for the capacitive-coupled STATCOM is defined as (13):

$$L = k \cdot \frac{E \cdot T_S}{\Delta I} \qquad (12) \qquad \left(\frac{1}{X_c - X_L}\right) = \frac{Q}{V_s^2} \qquad (13)$$

Where Q is the single phase reactive power of the load. $C_c = 1/\omega X_c$. Since $X_L \ll X_c$ in capacitive-coupled case, the coupling reactance keeps at capacitive.

III. SIMULATION RESULTS

Figs. 8 and 9 show the inductive-coupled and capacitive-coupled STATCOMs in 3-phase power system for simulation, where the system line-to-line voltage $V_{L-L(rms)}$ is 380V, source inductance L_s is 1mH, L_c is 12mH, C_c is 160μF and dc-link storage capacitance C_{dc} is 20mH respectively. Hysteresis PWM with a switching sampling frequency 5kHz is applied for both STATCOMs because it does not require additional PLL circuit. And the detail of the control scheme strategy will be presented in [6].

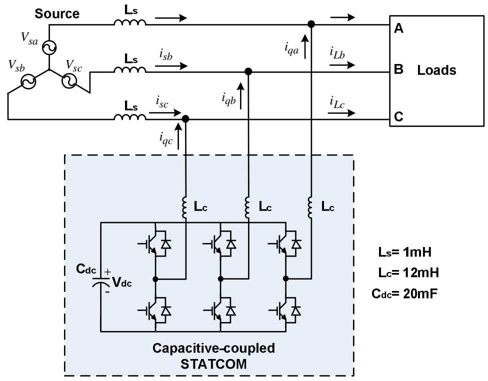

Fig. 8 Configuration of a 3-phase inductive-coupled STATCOM

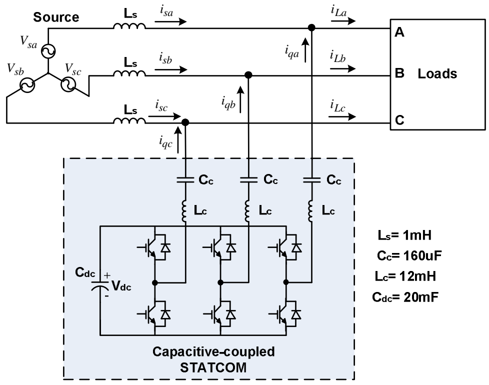

Fig. 9 Configuration of a 3-phase capacitive-coupled STATCOM

A. *Case I: Inductive, Balanced and Heavy Load Situation*

When the load is inductive, balanced and heavy, the system data before compensation are summarized in Table I. From Table II, when V_{dc} is 50V for the inductive-coupled STATCOM, the compensated results are not satisfactory. This is because V_{dc} is lower than the minimum V_{dc} required for two-level three phase inverter ($\sqrt{2} \cdot V_{L-L(rms)} = 539V$) [7]. This phenomenon is actually due to the turn on of the clamped diode which is paralleled with the IGBT switch when V_{dc} is too low. And the inverter has unexpected output current even there is no trigger signal for the IGBT. When V_{dc} is raised to 650V, the compensation results are acceptable, the displacement power factor and source current have been compensated into unity and balanced 13.18 A. The source current THD of 5.5% is within standard 16% [8].

For the proposed capacitive-coupled STATCOM as shown in Table II, it has better compensation results even though its V_{dc} is only 50V, which is 7.7% of that of the inductive-coupled structure (650V). The displacement power factor and source current have been compensated into unity and balanced 13.04 A. The source current THD is 2.5%, which is within standard 16% [8]. As a result, the required V_{dc} for the proposed capacitive-coupled STATCOM under inductive, balanced and heavy load can be greatly reduced compared with that of the conventional inductive-coupled STATCOM.

TABLE I

Case I. Before Compensation (3-phase inductive, balanced, heavy load)			
Phase	A	B	C
Displacement Power Factor	0.71	0.71	0.71
Source Current (RMS)	16.01 A	15.82 A	15.82 A
THD of Source Current (%)	0.20	0.20	0.19

B. *Case II: Inductive, Balanced and Light Load Situation*

When the load is inductive, balanced and light, the system data before compensation are summarized in Table III. From Table IV, when V_{dc} is 650V for the inductive-coupled case, the displacement reactive power has been compensated into unity, however, the source current THD are not satisfactory. This is caused by the switching noise generated into the system. Since the fundamental source current is small during light load, the switching noise effect to the source current THD will be large. The source current THD is deteriorated to 21.5%, which falls outside standard 16% [8].

For the proposed capacitive-coupled STATCOM, the required V_{dc} will be increased close to $\sqrt{2}\cdot v_{L-L(rms)}$ referring to Figs. 7b and c. Table IV illustrates that the fundamental reactive power is deteriorated into 0.27, and the STATCOM draws active current. This is because V_{dc} is too low (50V) for light load compensation, which agrees with its V-I characteristic. When V_{dc} is raised to 550V, the fundamental reactive power has been compensated to unity, but its unsatisfied source current THD (18.4%) are due to the same reason as that of the above inductive-coupled case.

The source current THD problem can easily be solved by increasing L_c value. Table IV shows that the source current THD has been significantly improved to 7.9% and 6.5% after L_c increases to 50mH. *Case II* simulation results show the required V_{dc} (550V) for the capacitive-coupled STATCOM increases a lot during light load situation, but its value is still less than that of the inductive-coupled STATCOM (650V).

TABLE III

Case II. Before Compensation (3-phase inductive, balanced, light load)			
Phase	A	B	C
Displacement Power Factor	0.994	0.994	0.994
Source Current (RMS)	2.17 A	2.15 A	2.18 A
THD of Source Current (%)	0.25	0.26	0.23

C. *Case III: Unbalanced Inductive Load Situation*

When the load is inductive and unbalanced, the system data before compensation are summarized in Table V. From Table VI, when V_{dc} is 650V for the inductive-coupled case, the displacement power factor and source current have been compensated into unity and balanced 10.24 A. The source current THD of 7% is within standard 16% [8].

For the proposed capacitive-coupled case, it has better compensation results even though its V_{dc} is only 400V, which is 61% of that of the inductive-coupled case (650V). The displacement power factor and source current have been compensated into unity and 9.21 A. The source current THD of 5% is within standard 16% [8]. As a result, *Case III* simulation results show that the required V_{dc} (400V) for the proposed capacitive-coupled STATCOM increase a lot during unbalanced load situation, but its value is still less than that of the inductive-coupled STATCOM (650V).

TABLE V

Case III. Before Compensation (3-phase unbalanced, inductive load)			
Phase	A	B	C
Displacement Power Factor	0.83	0.48	0.90
Source Current (RMS)	15.22 A	12.02 A	8.00 A
THD of Source Current (%)	0.20	0.22	0.30

D. *Case IV: Capacitive, Balanced and Heavy Load Situation*

When the load is capacitive, balanced and heavy, the system data before compensation are summarized in Table VII. From VIII, when V_{dc} is 450V for both STATCOMs, the compensated results are acceptable. The displacement power factor and source current have been compensated into unity and balanced 11.48 A. The source current THD of 5.2 % is within standard 16% [8]. These results are consistent with Figs. 7a and b that the required V_{inv} is close to V_s under capacitive and heavy load compensation, as the slope reactance X_L is small. In order to lower the V_{dc}, X_L can be increased. From Table VIII, when L_c is 50mH, the required V_{dc} can be lowered to 100V. The displacement power factor and source current have been compensated into unity and balanced 11.30 A. The source current THD of 1.20% is within standard 16% [8]. As a result, *Case IV* simulation results verify Figs. 7a and b in capacitive load compensation and the effect of reactance to the required V_{dc} level.

TABLE VII

Case IV. Before Compensation (3-phase capacitive, balanced, heavy load)			
Phase	A	B	C
Displacement Power Factor	0.70	0.70	0.70
Source Current (RMS)	14.90 A	15.05 A	15.04 A
THD of Source Current (%)	0.21	0.21	0.21

The above four cases verify the V-I characteristic analysis of the inductive-coupled and capacitive-coupled STATCOMs. For the capacitive-coupled case under inductive load, the dc-link requires the lowest and largest voltage level during full and no load operation, but its largest value is still less than the minimum dc-link voltage of the inductive-coupled case. Moreover, the unbalanced load situation increases the required dc-link voltage as well. Under capacitive load operation, both STATCOMs will have the same characteristic as that of the capacitive-coupled case under inductive load operation. Simulation results also verify the effect of coupling reactance to the required dc-link voltage level.

IV. CONCLUSION

Based on the theoretical analysis and simulation results, they verify that the proposed novel capacitive-coupled

STATCOM structure can lower the dc-link rating of the conventional inductive-coupled STATCOM. Thus, it benefits from the significant reduction of the system initial costs, switching loss and electromagnetic interference (EMI) problem. The modeling and V-I characteristic of the capacitive-coupled STATCOM is also proposed, studied and verified. This novel capacitive-coupled STATCOM can be modified and applied to different STATCOM architectures, such as diode-clamped multilevel inverters, flying capacitor multilevel inverter, cascading multilevel inverters, etc. for large capacity STATCOM (MVAR) circuit design. Moreover, the multilevel inverters can further reduce the switching harmonics generated into the system.

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TABLE II

Case I. After Compensation (3-phase inductive, balanced and heavy load)	Inductive-coupled STATCOM (V_{dc} = 50V, L_c = 12mH)			Inductive-coupled STATCOM (V_{dc} = 650V, L_c = 12mH)			Capacitive-coupled STATCOM (V_{dc} = 50V, L_c = 12mH)		
Phase	A	B	C	A	B	C	A	B	C
Displacement Power Factor	0.45	0.45	0.45	1.0	1.0	1.0	0.99	0.99	0.99
Source Current (RMS)	26.95 A	26.64 A	26.42 A	13.18 A	13.18 A	13.21 A	13.02 A	13.04 A	13.21A
THD of Source Current (%)	0.24	0.25	0.24	5.75	5.61	5.35	2.49	2.38	2.51
Compensating Current (RMS)	13.58A	13.33 A	13.19A	11.11A	11.14 A	10.95 A	12.90 A	13.10 A	12.90A

TABLE IV

Case II. After Compensation (3-phase inductive, balanced and light load)	Inductive-coupled STATCOM (V_{dc} = 650V, L_c = 12mH)			Capacitive-coupled STATCOM (V_{dc} = 50V, L_c = 12mH)			Capacitive-coupled STATCOM (V_{dc} = 550V, L_c = 12mH)		
Phase	A	B	C	A	B	C	A	B	C
Displacement Power Factor	1.0	1.0	1.0	0.27	0.27	0.27	1.0	1.0	1.0
Source Current (RMS)	3.47 A	3.51 A	3.55A	13.90A	14.17A	14.00A	3.49A	3.47A	3.52 A
THD of Source Current (%)	21.65	22.42	21.70	2.25	2.20	2.15	18.40	18.41	18.43
Compensating Current (RMS)	1.53A	1.60 A	1.59A	13.74A	13.96 A	13.77A	1.53A	1.47A	1.51A

TABLE IV (Continue)

Case II. After Compensation (3-phase inductive, balanced and light load)	Inductive-coupled STATCOM (V_{dc}= 650V, L_c= 50mH)			Capacitive-coupled STATCOM (V_{dc} = 550V, L_c = 50mH)		
Phase	A	B	C	A	B	C
Displacement Power Factor	1.0	1.0	1.0	1.0	1.0	1.0
Source Current (RMS)	2.47 A	2.47 A	2.43 A	2.50 A	2.59 A	2.54 A
THD of Source Current (%)	7.73	7.92	7.41	6.12	6.69	5.74
Compensating Current (RMS)	0.50A	0.50A	0.49A	0.46 A	0.46 A	0.46 A

TABLE VI

Case III. After Compensation (3-phase unbalanced inductive load)	Inductive-coupled STATCOM (V_{dc} = 650V, L_c = 50mH)			Capacitive-coupled STATCOM (V_{dc} = 400V, L_c = 50mH)		
Phase	A	B	C	A	B	C
Displacement Power Factor	1.0	1.0	1.0	1.0	1.0	1.0
Source Current (RMS)	10.24 A	10.24 A	10.14 A	9.21 A	8.83 A	9.70 A
THD of Source Current (%)	7.09	6.86	7.36	5.12	4.72	5.35
Compensating Current (RMS)	8.74A	11.47 A	4.42 A	8.61 A	11.37 A	4.36 A

TABLE VIII

Case IV. After Compensation (3-phase capacitive, balanced and heavy load)	Inductive-coupled and Capacitive-coupled STATCOMs (V_{dc} = 450V, L_c = 12mH)			Inductive-coupled and Capacitive-coupled STATCOMs (V_{dc} = 100V, L_c = 50mH)		
Phase	A	B	C	A	B	C
Displacement Power Factor	1.0	1.0	1.0	1.0	1.0	1.0
Source Current (RMS)	11.47 A	11.48 A	11.50 A	11.30 A	11.20 A	11.37 A
THD of Source Current (%)	5.40	5.02	5.14	1.19	1.21	1.19
Compensating Current (RMS)	10.93 A	10.90 A	10.70 A	11.30 A	11.34 A	11.19 A