Control Scheme of A Novel Capacitive-Coupled STATCOM

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***Abstract*-In this paper, a control scheme for a novel capacitive-coupled STATCOM in three-phase power system is proposed and analyzed. In order to maintain the dc-link voltage to a constant level, an active block diagram model is built. Based on this model, a novel dc-link voltage feedback control scheme is proposed and discussed. The proposed novel capacitive-coupled STATCOM is characterized by lower the dc-link rating of the conventional inductive-coupled STATCOM with good system compensation feature. Simulation results are given to prove the effectiveness of the control scheme together with the dc-link voltage feedback control in the novel capacitive-coupled STATCOM.**

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 control scheme for a novel capacitive-coupled STATCOM in three-phase power system is proposed and analyzed. In order to maintain the dc-link voltage, an active block diagram model is built for analysis. Based on this model, a novel dc-link voltage feedback control strategy is also proposed and discussed. Finally, simulation results are given to prove the effectiveness of the control scheme and the novel capacitive-coupled STATCOM.

II. PROPOSED NOVEL CAPACITIVE-COUPLED STATCOM

A. Theoretical Analysis of the Proposed Novel Capacitive-coupled STATCOM

With practical operation consideration, a novel capacitive-coupled STATCOM configuration is shown in Fig. 1. Figs. 2 and 3 show its single phase equivalent model and phasor diagram. V_s ,V_{inv} , I_q , I_{Lq} , X_L and X_C represent the power system RMS voltage, inverter output voltage, inject reactive current, load reactive current, coupling inductor reactance and capacitor reactance. From Figs. 2 and 3, the STATCOM can do compensation even V_{inv} is smaller than V_s . Since V_{inv} depends on the dc-link voltage (V_{dc}) level, if X_L and X_C are chosen appropriately, V_{dc} can be reduced significantly.

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

$$Q_{inv} = -Q_{in\_load} - Q_{coup\_cap} + Q_{coup\_ind} \quad (1)$$

$$V_{inv} I_q = -V_s I_{Lq} - I_q^2 X_c + I_q^2 X_L \quad (2)$$

,where Q_{inv} , Q_{ind_load} , Q_{coup_cap} and Q_{coup_ind} represent the inject reactive power, reactive power drawn by inductive load, reactive power caused by X_C , 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:

$$V_{inv} = V_s - I_q X_c + I_q X_L \quad (3)$$

Similarly, in ideal capacitive load reactive power compensation as shown in Fig. 3b, the proposed capacitive-coupled STATCOM can be can be expressed:

$$V_{inv} = V_s - I_q X_L \quad (4)$$

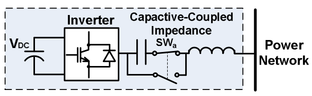

Fig. 1a Configuration of the capacitive-coupled STATCOM at inductive load

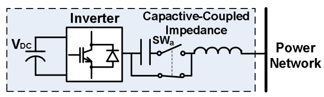

Fig. 1b Configuration of the capacitive-coupled STATCOM at capacitive load

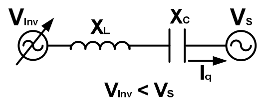

Fig. 2a Single phase equivalent model of the capacitive-coupled STATCOM at inductive load

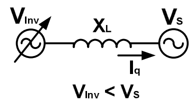

Fig. 2b Single phase equivalent model of the capacitive-coupled STATCOM at capacitive load

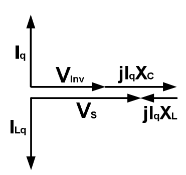

Fig. 3a Phasor diagram of the lossless capacitive-coupled STATCOM at inductive load

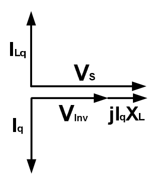

Fig. 3b Phasor diagram of the lossless capacitive-coupled STATCOM at capacitive load

B. Determination of Coupling Capacitance and Inductance [5]

For the capacitive-coupled STATCOM, the coupling inductance L_c can be chosen by (5), 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, which is chosen by (5), thus k is usually chosen between 0.4 ~ 0.6. Moreover, X_c for the capacitive-coupled STATCOM is defined as (6):

$$L = k \cdot \frac{E \cdot T_S}{\Delta I} \quad (5) \qquad \left(\frac{1}{X_c - X_L} \right) = \frac{Q}{V_s^2} \quad (6)$$

Where Q is the single phase reactive power of the load. $C_c = 1/\omega X_c$. Since $X_L << X_c$, the coupling impedance keeps at capacitive.

C. Control Scheme of the Proposed Novel Capacitive-coupled STATCOM

According to the generalized theory of instantaneous reactive power [6], [7], the instantaneous space vectors of the phase voltage, $\vec{v}$ and line current, $\vec{i}$ under *a-b-c* coordinates can be expressed as (7), while the instantaneous active power p and reactive power $\vec{q}$ are defined as (8) and (9) respectively:

$$\vec{v} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}_{abc}, \vec{i} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}_{abc}, \forall v_a, v_b, v_c, i_a, i_b, i_c \in \mathbb{R} \quad (7)$$

$$p = v \cdot i = v_a \cdot i_a + v_b \cdot i_b + v_c \cdot i_c \quad (8)$$

$$\vec{q} \equiv \vec{v} \times \vec{i} = \begin{bmatrix} v_b i_c - v_c i_b \\ v_c i_a - v_a i_c \\ v_a i_b - v_b i_a \end{bmatrix}_{abc} \quad (9)$$

Where "·" denotes the dot product and "×" denotes the cross product of vectors. Moreover, the instantaneous active and reactive power can also be expressed as:

$$\begin{aligned} p &= \bar{p} + \tilde{p}, \ \tilde{p} = \tilde{p}_{2\omega} + \tilde{p}_h \\ \vec{q} &= \vec{\bar{q}} + \vec{\tilde{q}}, \ \vec{\tilde{q}} = \vec{\tilde{q}}_{2\omega} + \vec{\tilde{q}}_h \end{aligned} \quad (10)$$

where $\bar{p}$ is the dc portion of instantaneous active power, $\vec{\bar{q}}$ is an instantaneous imaginary power space vector with all elements in its dc value. $\bar{p}$ and $\vec{\bar{q}}$ are originating from the symmetrical fundamental component, where $\bar{p}$ is the average active power delivered, and $\vec{\bar{q}}$ is the average imaginary power circulating between the phases. $\tilde{p}$ is the oscillating portion of p, and $\vec{\tilde{q}}$ has all the elements in the corresponding oscillating portion of $\vec{q}$. $\tilde{p}$ and $\vec{\tilde{q}}$ are the ripple active and imaginary power that are results of harmonics and asymmetrical components, $\tilde{p}_{2\omega}$, $\tilde{q}_{2\omega}$ are 2ω components caused by asymmetrical three-phase fundamental components (negative sequence active and reactive), $\tilde{p}_h$, $\tilde{q}_h$ are the oscillating active and imaginary power components caused by harmonics.

For the reactive power compensation objective, the compensating instantaneous reactive current for each phase can be calculated as (11):

$$i_{qa} = \frac{(q_b v_c - q_c v_b)}{\|\vec{v}\|^2}, i_{qb} = \frac{(q_c v_a - q_a v_c)}{\|\vec{v}\|^2}, i_{qc} = \frac{(q_a v_b - q_b v_a)}{\|\vec{v}\|^2} \quad (11)$$

where $\|\vec{v}\| = \sqrt{v_a^2 + v_b^2 + v_c^2}$

However, under the unbalanced load condition, it is not only $\vec{q}$ containing 2ω components, but p also contains 2ω components. Therefore, balanced sinusoidal currents on the source side can only be achieved by compensating both $\vec{q}$ and $\tilde{p}_{2\omega}$. However, the compensator would require a larger capacity energy storage element in this control scheme. This is because the compensator needs to compensate the unbalanced $\tilde{p}_{2\omega}$ besides $\vec{q}$. For a system having unbalanced load current without harmonics, the compensating instantaneous current can be calculated by (12), where $\tilde{p} = \tilde{p}_{2\omega}$ can be extracted out by using a band-pass filter. For a system having harmonics problem as well, $\tilde{p} = \tilde{p}_{2\omega} + \tilde{p}_h$ which can be extracted out with the help of a low-pass filter:

$$i_{ca} = \frac{\tilde{p} v_a + (q_b v_c - q_c v_b)}{\|\vec{v}\|^2}, \ i_{cb} = \frac{\tilde{p} v_b + (q_c v_a - q_a v_c)}{\|\vec{v}\|^2},$$

$$i_{cc} = \frac{\tilde{p} v_c + (q_a v_b - q_b v_a)}{\|\vec{v}\|^2} \quad (12)$$

For applying the 3DSVM or 3D direct PWM voltage tracking control method [8] - [10] to the capacitive-coupled STATCOM, the inverter reference voltage in each phase can be calculated by (3) with the help of (12) and a Phase Lock-Loop (PLL) for synchronization. In addition, for applying the simple current tracking Hysteresis PWM control method, the inverter reference current can be calculated by (12) with no PLL is required, even though both PWM schemes can obtain the same compensation results. Since the coupling components of the novel capacitive-coupled STATCOM are in 2nd order, instead of the 1st order of the conventional inductive-coupled case, it is easier to just track the required inject reference current directly, instead of determining the reference voltage first, and then with further calculation of the 2nd order coupling components reactance. Moreover, the temperature and other environmental factors affect the coupling reactance value. In the following, only the results of Hysteresis PWM method are given and that of the 3D SVM or 3D direct PWM, etc. will not be presented in this paper.

D. DC-link Voltage Feedback Control with PI Controller

Fig. 4 shows an active power block model for STATCOM. If the STATCOM outputs reference without error, it can be viewed as a unity block. The closed-loop transfer function can be expressed as:

$$H(s) = \frac{p_{dc}(s)}{M(s)} = \frac{s^2(s+a)}{\Delta(s)} \quad (13)$$

Where $\Delta(s) = s^3 + as^2 + aK_I s + aK_{II}$ (14)

$M(s) = -P_{loss}(s)$ (15)

Since there are two zeros in $H(s)$, V_{dc} will tend to its reference value at steady-state. By Routh-Hurwitz criterion, the closed-loop system is stable if $aK_I > K_{II}$. $\Delta(s)$ can be factorized in the form:

$$\Delta(s) = (s + p_1)(s^2 + 2\xi\omega_n s + \omega_n^2) \quad (16)$$

$$2\xi\omega_n + p_1 = a\,,\ \omega_n^2 + 2\xi\omega_n p_1 = aK_I\,,\ \omega_n^2 p_1 = aK_{II} \quad (17)$$

With the transient response consideration of a unit-step signal input to dc-link energy change $e(t)$ and STATCOM absorbed active power $p_{STATCOM}(t)$, the PI controller gains K_I and K_{II} can be designed.

The ISE of the $e(t)$ can be expressed as an index J_1. Applying Parseval's theorem, J_1 is:

$$J_1 = \frac{a^3 + p_1\omega_n^2}{2p_1\omega_n(a - p_1)(ap_1 + \omega_n^2)} \quad (18)$$

For minimization of the steady-state error of $p_{STATCOM}(t)$, the ISE of $e_{STATCOM}(t)$ is.

$$J_2 = \int_0^\infty e_{STATCOM}^2(t)\,dt = \frac{a^2}{4\xi\omega_n} + \frac{a^2(a - \xi\omega_n)}{a^2 - 2a\xi\omega_n + \omega_n^2} \quad (19)$$

By solving $\frac{\partial J_2}{\partial \xi} = 0$, the minimum point ξ_{min} inside $2\xi\omega_n < a$ or p_1 is positive is given as:

$$\xi_{min} = \frac{(a^2 + \omega_n^2)(a - \sqrt{a^2 - \omega_n^2})}{2\omega_n^3} \quad (20)$$

$$\omega_n < \sqrt{\frac{\sqrt{5} - 1}{2}}\,a \approx 0.786a \quad (21)$$

With (17), (18) and (20), the minimum ω_n by setting $\frac{dJ_1}{d\omega_n} = 0$ yields,

$$\omega_n \approx 0.6298a \quad (22)$$

Since (22) agrees $\omega_n < 0.786a$ (21), p_1 is positive, so that the system is stable.

Substitute $\omega_n = 0.6298a$ into (20) yields,

$$\xi \approx 0.624 \quad (23)$$

When a trends larger, the integral term effect will be too large and significant, which will deteriorate the system response. Finally,

$$K_I = 0.565a\,,\ K_{II} = 0.00849a^2 \quad (24)$$

Since (24) satisfies the stability requirement $aK_I > K_{II}$, the closed-loop system will be stable. However, it should be noted that (24) is not a unique solution. Since there is also a trade-off between dc-link voltage variation, dc storage capacitance and transient response, the controller PI gains can be designed under the system different specific requirement. The filter frequency a affects the harmonics contents generated and dc-link transient variation. The larger the a value, the larger the current harmonics and the smaller the dc-link voltage transient variation, and vice-versa.

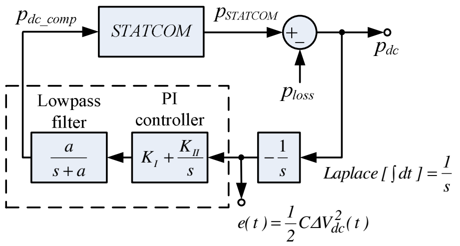

Fig. 4 Active power block model for STATCOM

E. Control Block Diagram Model of the Proposed Novel Capacitive-coupled STATCOM

The instantaneous power theory [6], [7] is applied for calculating and compensating for the instantaneous reactive and unbalanced active current of a three-phase STATCOM system. Fig. 5 shows a control block diagram of the proposed novel capacitive-coupled STATCOM with dc-link voltage feedback control. First of all, the source voltage V_s, load current i_L, compensating current i_c and dc-link voltage V_{dc} are sampled with a fixed frequency of 10kHz. The measured V_{dc} and its voltage reference V_{dc}^* are fed into a PI controller, which yields $\overline{P}_{dc\_comp}$, the dc-link variation compensating power. The instantaneous load reactive power $\vec{q}_L$ and ripple active power $\tilde{P}_L$ are then added together with $\overline{P}_{dc\_comp}$ for reference current i_c^* calculation. Subtracting the i_c from i_c^* yields the compensating current error Δi_c. The PWM switching signals are determined by comparing the compensating current error Δi_c with a hysteresis band (±H). Thus, the required compensating current will be generated into the system for compensation.

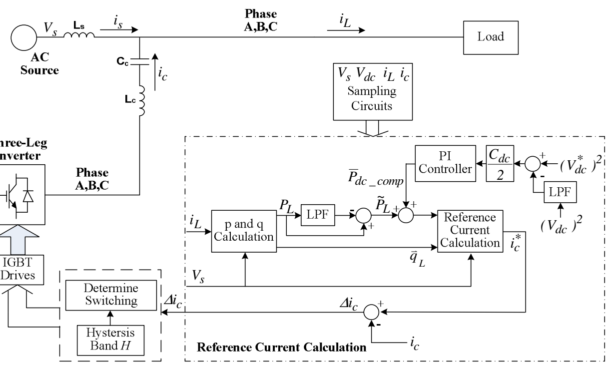

Fig. 5 Control block diagram model of the capacitive-coupled STATCOM with dc-link voltage control.

III. SIMULATION RESULTS

Fig. 6 shows the proposed capacitive-coupled STATCOM configurations 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, C_c is 160μF, L_c is 50mH and V_{dc} is set to 450V initially for unbalanced load situation [5], and dc-link storage capacitance C_{dc} is 20mH respectively. The STATCOM is controlled by Hysteresis PWM with 5kHz switching sampling frequency, where $a = 2\pi 25$ rad/s and PI gains K_I and K_{II} is designed (24). The simulation studies have been carried out using PSCAD/EMTDC. In the following, simulation results will be illustrated into: *Case I*, Unbalanced inductive load with dc-link voltage control, *Case II*, Unbalanced capacitive load with dc-link voltage control.

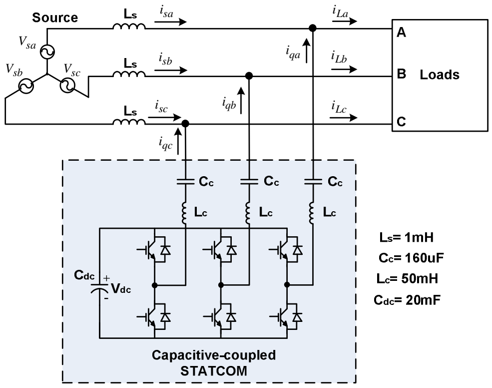

Fig. 6 Configuration of a 3-phase capacitive-coupled STATCOM

A. *Case I: Unbalanced Inductive Load Situation with DC-link Voltage Control*

When the load is inductive and unbalanced, the 3-phase source voltage and current before compensation are shown in Fig. 7a, and the system data are summarized in Table I. From Fig. 7b and Table II, the displacement power factor and source current have been compensated into unity and approximately balanced from unbalanced load current. The source current THD after compensation is around 6%, which is within standard 16% [11]. Fig. 7b also indicated the effectiveness of the dc-link voltage feedback control, as V_{dc} trends to its reference value (450V).

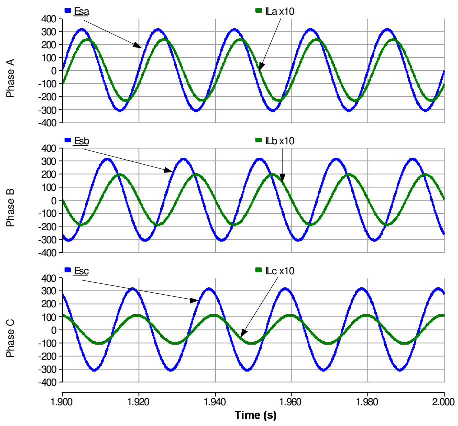

Fig. 7a 3-phase source voltage and unbalanced source current (Before compensation)

TABLE I

Case I. Before Compensation (3-phase unbalanced, inductive load with dc-link voltage control)			
Phase	A	B	C
Displacement Power Factor	0.89	0.49	0.93
Source Current (RMS)	16.70 A	13.54 A	7.67 A
THD of Source Current (%)	0.21	0.18	0.27

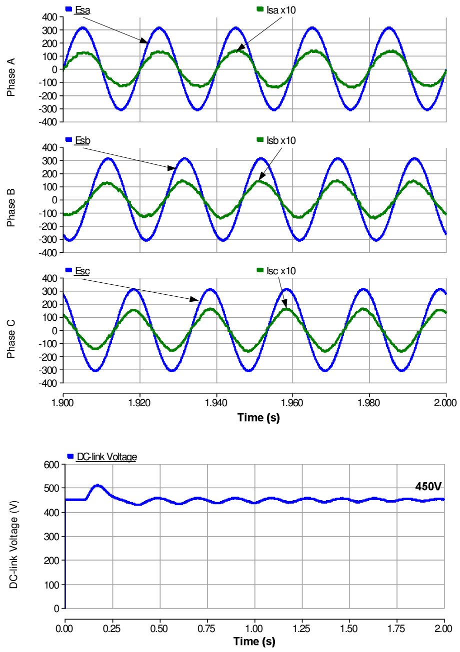

Fig. 7b 3-phase source voltage, source current and dc-link voltage (After compensation)

TABLE II

Case I. After Compensation (3-phase unbalanced, inductive load with dc-link voltage control)			
Phase	A	B	C
Displacement Power Factor	1.0	1.0	1.0
Source Current (RMS)	9.78 A	9.31 A	10.52 A
THD of Source Current (%)	6.10	5.64	5.69
Compensating Current (RMS)	8.55 A	12.48 A	4.52 A

B. *Case II: Unbalanced Capacitive Load Situation with DC-link Voltage Control*

When the load is capacitive and unbalanced, the 3-phase source voltage and current before compensation are shown in Fig. 8a, and the system data are summarized in Table III. From Fig. 8b and Table IV, the displacement power factor and source current have been compensated into unity and approximately balanced from unbalanced load current. The source current THD after compensation is around 8.50%, which is within standard 16% [11]. Fig. 8b also indicated that V_{dc} can be controlled to its reference value (450V).

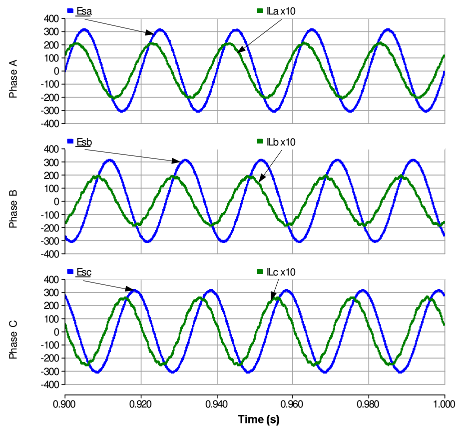

Fig. 8a 3-phase source voltage and unbalanced source current (Before compensation)

TABLE III

Case II. Before Compensation (3-phase unbalanced, capacitive load with dc-link voltage control)			
Phase	A	B	C
Displacement Power Factor	0.80	0.54	0.63
Source Current (RMS)	14.51 A	13.10 A	17.93 A
THD of Source Current (%)	0.21	0.18	0.27

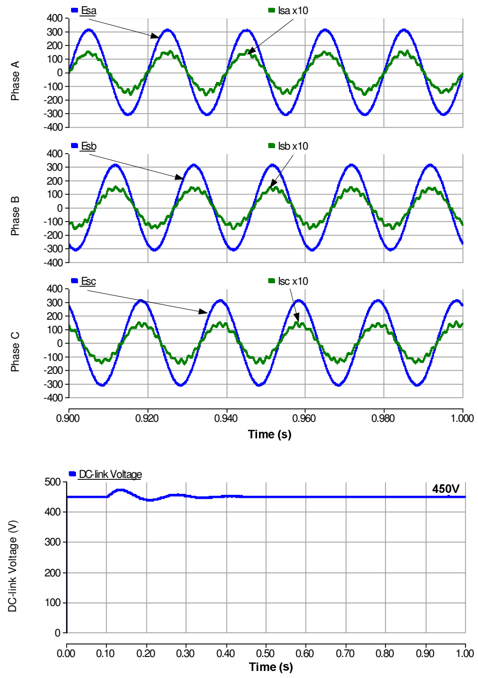

Fig. 8b 3-phase source voltage, source current and dc-link voltage (After compensation)

TABLE IV

Case II. After Compensation (3-phase unbalanced, capacitive load with dc-link voltage control)			
Phase	A	B	C
Displacement Power Factor	1.0	1.0	1.0
Source Current (RMS)	10.14 A	9.91 A	9.85 A
THD of Source Current (%)	7.60	8.50	8.96
Compensating Current (RMS)	8.95 A	11.74 A	13.97 A

Both *Cases I and II* simulation results verify the proposed control scheme and the unbalanced, inductive and capacitive load compensation capability of the proposed novel STATCOM. They also indicated the effectiveness of the proposed dc-link voltage feedback control. In order to further reduce the switching harmonics generated into the system and also lower the dc-link voltage required, STATCOM based on cascaded multilevel inverters [2] – [4] can be applied.

Compared with the balanced load simulation results presented in [5], these results also show that the required V_{dc} (450V) increases a lot during unbalanced load (inductive or capacitive) situation, because of the $\tilde{p}_{2\omega}$ term. The larger the load unbalance, the larger $\tilde{p}_{2\omega}$ and the larger V_{dc} required. But V_{dc} level is 83% of the minimum V_{dc} required for two-level three phase inverter ($\sqrt{2}\cdot V_{L-L(rms)} = 539V$) of the inductive-coupled STATCOM [5]. Thus, the proposed novel STATCOM can lower the dc-link rating of the conventional inductive-coupled STATOM. Moreover, the compensation results are satisfactory.

IV. CONCLUSION

Based on the theoretical analysis and simulation, they verify that the viability and effectiveness of the proposed control scheme with the dc-link voltage feedback of the proposed novel capacitive-coupled STATCOM. The novel STATCOM is characterized by a lower dc-link voltage required, which benefits by reducing the cost, switching loss and electromagnetic interference (EMI) problems. Cascading multilevel inverters is also a choice for large capacity STATCOM (MVAR) circuit design and switching harmonics reduction purposes. And the detail of capacitive-coupled STATCOM based on cascaded multilevel inverters will be presented in future publication.

ACKNOWLEDGMENT

The authors would like to thank the *Science and Technology Development Fund*, *Macao SAR Government* and *University of Macau* for their financial supports.

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