International Journal of Advanced Research Methodology in Engineering & Technology, ISSN 2456-6446
Volume 1, Issue 4, July 2017

A Hybrid-STATCOM with broad compensation range and lower DC-Link voltage

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Abstract— **This paper proposes a hybrid static synchronous compensator (hybrid-STATCOM) in a three-phase power transmission system that has a broad compensation range and low dc-link voltage. In this paper, the circuit configuration of traditional and capacitive STATCOM are introduced first. The system parameter design for the hybrid STATCOM is then proposed on the basis of consideration of the reactive power compensation range. Because of the low dc-link voltage, the system costs can be reduced considerably. Finally, simulation is carried out in MATLAB to verify the wide compensation range and low dc-link voltage characteristics and the good dynamic performance of the proposed hybrid-STATCOM.**

Keywords— hybrid static synchronous compensator (hybrid STATCOM), static synchronous compensator (STATCOM), broad compensation range, low DC-link voltage

I. INTRODUCTION

The control of voltage and reactive power is of paramount importance in power system operation. The large reactive current in transmission systems lowers the stability of a power system and increases transmission losses. Reactive power compensators can be used as one of the solutions for this issue. While reactive power does not provide useful work, it is crucial for AC transmission and distribution systems and many other types of customer loads. Therefore, actual power systems need both real and reactive power to function properly. Increasing var load diminishes the ability of the system to deliver real power and perform useful work. In severe cases, a high var load can shift the voltage and current so much that it reduces the power systems delivery potential so that almost no active power can be delivered. There can also be other undesirable effects such as increased equipment heating and system losses.

Series and shunt Var compensation are employed to improve the natural electrical characteristics of ac power systems. Series compensation modifies the transmission or distribution system parameters, while shunt compensation alters the equivalent impedance of the load. In both cases, the reactive power that flows through the system can be successfully controlled and thereby improving the performance of the ac power system. Static Var compensators (SVCs) are traditionally used to dynamically compensate reactive currents as the loads differ from time to time. Due to the resonance problems, harmonic current injection, and slow response of SVCs , static synchronous compensators (STATCOMs) were developed for reactive current compensation with faster response, less harmonic current injection, and superior performance. However, the STATCOMs or APFs normally require multilevel structures in a medium- or high voltage level transmission system to lessen the high-voltage stress across each power switch and dc-link capacitor, which escalates the initial and operational costs of the system and also increases the control complexity. Later, series-type capacitive coupled STATCOMs (C-STATCOMs) were recommended to reduce the system dc-link operating voltage requirement but their system performances can significantly deteriorate when the required compensating reactive power is outside their compensation range.

To overcome the shortcomings of various reactive power compensators for transmission systems, this paper proposes a hybrid-STATCOM with the distinctive characteristics of a much wider compensation range than C-STATCOM and a much lower dc-link voltage than traditional STATCOM.

II. SYSTEM MODELING

The hybrid-STATCOM consists of a thyristor controlled LC part which is connected in series with an active inverter part, as shown in Fig.1. The thyristor controlled LC part produces a wide range of compensating reactive power and a huge voltage drop between the system inverter voltage which allows the active inverter part to continue to operate at a lower DC link voltage level. The performance of the thyristor controlled LC part is improved with the help of active inverter part because of its small rating and its ability to absorb the harmonics currents produced by the TCLC part. The active inverter part also helps in avoiding the resonance problem as well as mistuning of firing angles.

Fig.1 presents the system configuration of hybrid STATCOM, in which the subscript represents phase a, b, and c respectively.

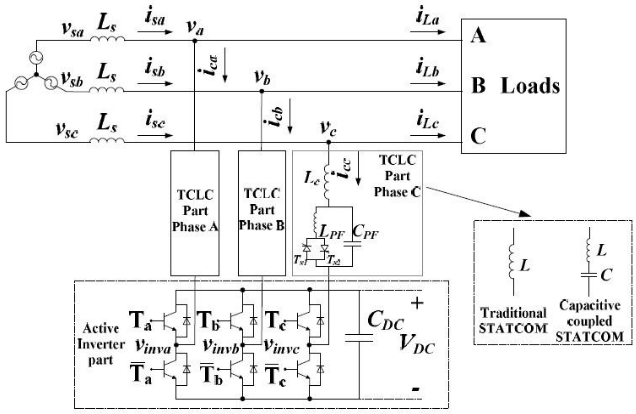

Figure 1. System configuration for hybrid STATCOM

V_{sx} and V_x stands for the source and load voltages. The load, source, and compensating currents are represented by i_{Lx}, i_{sx} and i_{cx} respectively. The impedance of the transmission line is Ls. The TCLC part mainly contains a parallel capacitor C_{PF} and a thyristor triggered reactor L_{PF} . The TCLC part is connected to the transmission line with the help of a coupling inductor L_c. The purpose of TCLC part is to supply a broad and continuous capacitive and inductive compensating reactive power that is regulated by controlling the α_x (firing angles of the thyristors. The active inverter part comprises of a voltage source inverter together with a DC link capacitor C_{dc}, and rating of the active inverter part is kept as small as possible to enhance the performance of the thyristor controlled LC section. Also, coupling components used for the traditional STATCOM and C STATCOM are also shown Fig.1.

The hybrid STATCOM is used to supply the exact amount of reactive power as the loadings (Q_{Lx}) have consumed. The reactive power should be supplied in such a manner that the compensating reactive power should cancel out the reactive power consumed by the loads (Q_{cx} =-Q_{Lx}). The reactive power supplied by the thyristor controlled part (Q_{TCLC}) together with active inverter part (Q_{invx}) constitutes the total reactive power supplied by the hybrid STATCOM (Q_{cx}). Therefore, the expression relating Q_{TCLC}, Q_{Lx} and Q_{invx} can be mathematically shown as

$$Q_{Lx} = -Q_{cx} = -(Q_{TCLC} + Q_{in\vartheta x}) \qquad (1)$$

The reactive powers mentioned in the above equation can be rewritten in terms of voltages and currents as

$$Q_{Lx} = V_x I_{Lqx} = -(X_{TCLC}(\alpha_x) I_{cqx}^2 + V_{in\vartheta x} I_{cqx}) \quad (2)$$

where α_x is the corresponding firing angle and $X_{TCLC}(\alpha_x)$ is the coupling impedance of the thyristor controlled LC part. V_{invx} and V_x represents the root mean square value of the inverter voltage and coupling point; and I_{cqx} and I_{Lqx} are the root mean square value of the compensating and load reactive currents, where the load and compensating reactive currents are in opposite polarity (I_{Lqx} = -I_{cqx}). Applying this to equation 2, we get

$$V_{in\vartheta x} = V_x + X_{TCLC}(\alpha_x) I_{Lqx} \qquad (3)$$

The thyristor controlled LC part impedance $X_{TCLC}(\alpha_x)$ can be mathematically expressed as

$$X_{TCLC}(\alpha_x) = \frac{\pi X_{L_{PF}} X_{C_{PF}}}{X_{C_{PF}}(2\pi - 2\alpha_x + sin2\alpha_x) - \pi X_{L_{PF}}} + X_{L_c} \qquad (4)$$

where X_{CPF} ;X_{LPF} and X_{Lc} represents the fundamental impedances of C_{PF} ;L_{PF} and L_c respectively. From equation 4, it is clear that the thyristor controlled LC part impedance is regulated by the firing angle α_x. The minimum capacitive and inductive impedances of the thyristor controlled LC part can be acquired by substituting the firing angles α_x = 90 and α_x = 180, respectively. In the following analysis, the minimum value for impedances means its absolute value. The minimum capacitive ($X_{Cap(min)} < 0$) and inductive ($X_{ind(min)} > 0$) thyristor controlled LC part impedances can be shown as

$$X_{Cap(min)}(\alpha_x = 180^o) = -X_{C_{PF}} + X_{L_C} \qquad (5)$$

$$X_{Ind(min)}(\alpha_x = 90^o) = \frac{X_{L_{PF}} X_{C_{PF}}}{X_{C_{PF}} - X_{L_{PF}}} + X_{L_C} \qquad (6)$$

In ideal case, $X_{TCLC}(\alpha_x)$ is regulated to be V_x~ $X_{TCLC}(\alpha_x)$ I_{Lqx}, so that the required minimum inverter voltage (V_{invx}=0) can be achieved as shown in equation 3. By this way, the switching noise and switching loss can be greatly reduced. A small inverter voltage $V_{invx(min)}$ is maintained to absorb the harmonic current produced by the thyristor controlled LC part and thereby preventing the resonance problem and mistuning firing angles of thyristors. The inverter voltage V_{invx} will be marginally improved to further expand the compensation range if the loading inductive current or capacitive current is out of the thyristor controlled LC part compensation range.

Traditional and capacitive coupled STATCOM are coupled with the transmission line with fixed impedance X_L and X_C - 1/XL, as shown in Fig.1. The inverter voltage V_{invx} for traditional STATCOM and C STATCOM can be mathematically expressed as

$$V_{in\vartheta x} = V_x + X_L I_{Lqx} \qquad (7)$$

$$V_{in\vartheta x} = V_x - (X_C - \frac{1}{X_L}) I_{Lqx} \qquad (8)$$

III. DESIGN PARAMETERS

Hybrid STATCOM achieves its superior performance because of the proper coordination between both TCLC part and active inverter part. In this chapter, the design parameters which enhances the performance of hybrid STATCOM is explained in detail. The thyristor triggered LC part is designed to achieve maximum reactive power compensation range (for L_{PF} and C_{PF}). The potential resonance problem is avoided by the proper design of L_c whereas mistuning of the firing angle of thyristor triggered LC part is taken care of by active inverter part.

A. Design of L_{PF} and C_{PF}

The objective of the thyristor triggered L C part is to supply the same amount of compensation reactive power $Q_{cx,TCLC}(\alpha_x)$ as the reactive power consumed by the loads Q_{Lx} but with opposite polarity. Therefore, L_{PF} and C_{PF} are designed to supply maximum inductive and capacitive reactive power. The compensation reactive power Q_{cx} can be mathematically expressed in terms of thyristor triggered LC impedance $X_{TCLC}(\alpha_x)$ as

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

where V_x is root mean square value of load voltage and $X_{TCLC}(\alpha_x)$ is the impedance of the thyristor controlled LC part. In equation 9, when $X_{TCLC}(\alpha_x) = X_{Cap(min)}(\alpha_x = 180^o)$ and $X_{TCLC}(\alpha_x) = X_{Ind(min)}(\alpha_x = 90^o)$, the thyristor triggered LC part supplies the maximum capacitive and inductive compensation reactive power which are represented by $Q_{cx(MaxCap)}$ and $Q_{cx(MaxInd)}$ respectively.

$$Q_{cx(MaxCap)} = -\frac{V_x^2}{X_{C_{PF}} - X_{L_{c)}}} \qquad (10)$$

$$Q_{cx(MaxInd)} = \frac{V_x^2}{\frac{X_{L_{PF}} X_{C_{PF}}}{X_{C_{PF}} - X_{L_{PF}}} + X_{L_C}} \qquad (11)$$

where $X_{Ind(min)}$ and $X_{Cap(min)}$ represents minimum inductive and capacitive impedance obtained from equation 5 and 6, respectively. C_{PF} and L_{PF} can be obtained by loading maximum inductive $Q_{Lx(MaxInd)}$ ($=-Q_{cx(MaxCap)}$) and capacitive $Q_{Lx(MaxCap)}$ ($=-Q_{cx(MaxInd)}$) reactive power in order to compensate for the loading reactive power consumed by the loads. Therefore, based on equation 10 and 11, mathematical equation of C_{PF} and L_{PF} can be obtained as

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

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

where V_x is the root mean square load voltage and w is fundamental angular frequency.

B. Design of Coupling Inductor L_c

The design purpose of coupling inductor L_c to tune the resonance points to diverge from the dominated harmonic orders $n_d = 6n \pm 1^{th}$ (n= 1,2,3...) to evade the resonance problem. Both thyristors (T_{x1} and T_{x2}) for each phase of thyristor triggered LC part can be seen as a pair of bidirectional switches that produce lower order harmonic currents when the switch changes its states from ON position to OFF position and vice-versa. It can be simplified to single phase equivalent circuit which is shown in fig.2.

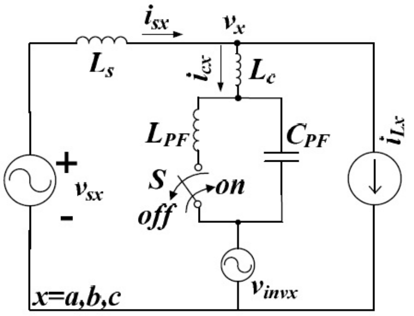

Figure 2. Simplified equivalent circuit of single-phase hybrid STATCOM

From fig.2, when the switch S is on OFF position, the thyristor triggered LC part can be considered as working in LC mode which means L_c is in series with C_{PF}. On the contrary, when the switch S is switched ON, the thyristor triggered LC part is working in LCL mode which means L_c is in series with the combination of C_{PF} in parallel with L_{PF}. The thyristor triggered LC part harmonic impedances for both LC mode and LCL mode at various harmonic order n can be mathematically expressed as

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

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

It is evident from equation 14 and 15, that there is a presence of two series resonance points n_1 at $X_{LC,n}(n_1) = 0$ and n_2 at $X_{LCL,n}(n_2) = 0$ and a parallel resonance point n_3 at $X_{LCL,n}(n_3) = +1$. The objective is to design L_c so as to tune the resonance points n_1 and n_2 to diverge from the dominant harmonic orders $n_d = 6n \pm 1^{th}$(n= 1,2,3...) or approach near the $3n^{th}$ order. Based on all these analysis , the criteria for designing L_c can be mathematically expressed as

$$L_c = \frac{1}{(\omega n_1)^2 C_{PF}} \qquad (16)$$

$$L_c = \frac{1}{(\omega n_2)^2 C_{PF} - 1/L_{PF}} \qquad (17)$$

$$n_3 = \frac{1}{\sqrt{L_{PF} C_{PF} \omega^2}} \qquad (18)$$

C_{PF} and L_{PF} which was designed earlier should also satisfy equation 18. For this project, $n_1 = 3.6$, $n_2 = 3.9$, and $n_3 = 1.5$ are selected.

C. Design of DC-Link Voltage V_{DC}

Traditionally V_{DC} of the STATCOM was designed to compensate for the maximum loading reactive power. But V_{DC} of Hybrid-STATCOM is designed with the objective of solving the firing angle mistuning problem of thyristor triggered LC part so that the source reactive power is kept constant and close to zero. Refining equation 3, inverter voltage (V_{invx}) can also be obtained as

$$V_{in\vartheta x} = V_x[1 + \frac{Q_{Lx}}{Q_{cx,\top CLC}(\alpha_x)}] \tag{19}$$

where Q_{Lx} and $Q_{cx,TCLC}(\alpha_x)$ represents load reactive power and thyristor triggered LC part compensating reactive power respectively and V_x is the root mean square value of the load voltage. Substituting equation 19 in $V_{DC}=(6)^{½}\,|V_{invx}|$, the essential DC link voltage V_{DC} can be mathematically expressed as

$$V_{DC} = \sqrt{6}V_x|1 + \frac{Q_{Lx}}{Q_{cx,\top CLC}(\alpha_x)}| \tag{20}$$

In an ideal case, the compensating reactive power of thyristor triggered LC part $Q_{cx,TCLC}(\alpha_x)$ is controlled to be equal to the reactive power consumed by the loads Q_{Lx} so that the necessary $V_{DC} = 0$. But, in practical case, $Q_{cx,TCLC}(\alpha_x)$ and Q_{Lx} will have some difference because of the firing angle mistuning problem. The worst scenario of mistuning Q_{Lx}= $Q_{cx,TCLC}(\alpha_x)$ ratio can be estimated to design the minimum V_{DC} value. Finally, a marginally greater V_{DC} value can be selected.

IV. CONTROL STRATEGY

Control strategy of hybrid-STATCOM is divided into two sections which are thyristor triggered LC part control and active inverter part control.

A. *Control of Thyristor Controlled LC Part*

Different from the traditional SVC control which is based on the conventional definition of reactive power, the thyristor controlled LC part control is based on the instantaneous pq theory. The thyristor triggered LC part is primarily used to regulate the reactive current with the controllable thyristor triggered LC part impedance X_{TCLC}. The control signals to trigger the thyristor triggered LC part can then be produced by comparing the θ_X (phase angle of load voltage V_x) with firing angle α_x . θ_X can be acquired with the help of a phase lock loop (PLL).

B. *Control of Active inverter part*

Instantaneous active and reactive current i_d - i_q method is used for active inverter part to enhance the overall performance of hybrid STATCOM for various voltage and current conditions. Primarily, active inverter part is employed to enhance the thyristor triggered LC part characteristic by restricting the compensating current i_{cx} to its reference value i^*_{cx} so as to avoid the resonance problem, the mistuning problem and the harmonic problem.

V. RESULTS AND DISCUSSIONS

Fig.3 and fig.4 shows the load voltage and load current of Hybrid-STATCOM respectively. The load current and load voltage waveforms are perfectly balanced, which means that the reactive power compensation of the hybrid-STATCOM is fully functional.

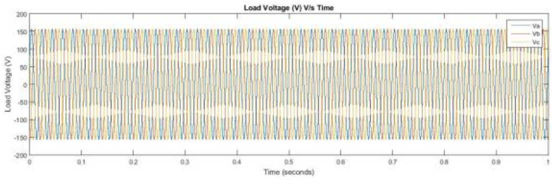

Figure 3. Load voltage of Hybrid-STATCOM

Fig.5 shows different reactive powers such as load, source and compensating reactive power under different loading conditions. It is evident from fig.5 that the source reactive power is almost constant and equal to zero. This is because of the presence of hybrid-STATCOM which supplies for the reactive power consumed by the loads and thereby enabling the source reactive power not to participate in the reactive power compensation. Fig.6 shows the variation of source current under different loading conditions. The magnitude of the source current varies because the loading are not purely capacitive and inductive. It is evident from fig.6,that the magnitude of the source current is minimum for the capacitive load and maximum for the heavy inductive load. The variation of load voltage under different loading conditions is shown in fig.7. The voltage waveform is free of any disturbance and magnitude variations which indicates the superior performance of the hybrid-STATCOM.

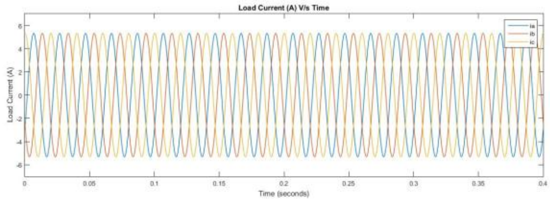

Figure 4. Load current of Hybrid-STATCOM

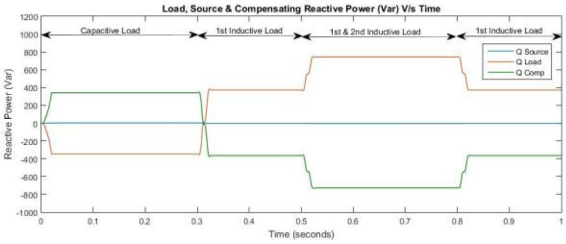

Figure 5. Load, Source and Compensating Reactive power for the Hybrid-STATCOM

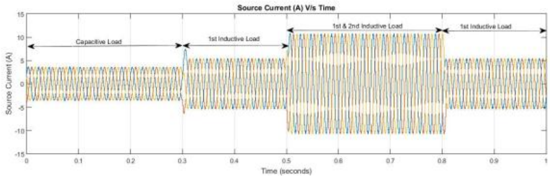

Figure 6. Source current of Hybrid-STATCOM (different load conditions)

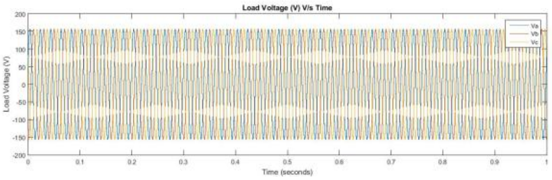

Figure 7. Load voltage of Hybrid-STATCOM (different load conditions)

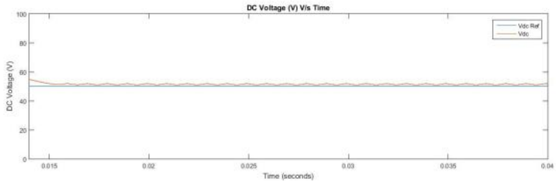

Figure 8. DC Link voltage of Hybrid-STATCOM

Fig.8 shows the DC link voltage of the hybrid STATCOM. The DC link voltage of hybrid STATCOM is minimum (50V) when compared with both traditional and CSTATCOM. This reduces the overall system cost drastically.

VI. CONCLUSION

Simulation of hybrid-STATCOM has been successfully completed using MATLAB simulink software. Also simulation of traditional STATCOM as well as C-STATCOM is also carried out to analyse the three models deeply. From the simulation results, it is evident that the performance of the hybrid-STATCOM is superior than the traditional and C-STATCOMs. Hybrid-STATCOM is realized by successfully coordinating both TCLC part and active inverter part. With this, the major problems faced in the systems such as resonance problem, harmonic current injection problem and firing angle mistuning problem of thyristors etc are avoided. The hybrid-STATCOM has been tested under different loading conditions such as capacitive loading, inductive light loading and inductive heavy loading. The reactive power compensation capability of hybrid-STATCOM is very high for different loading conditions as well. The superior performance of the hybrid-STATCOM is because of the design parameters included in the hybrid-STATCOM model. Also the system cost of the hybrid-STATCOM will be less when compared with both Traditional and C-STATCOM. This is because of the fact that the DC link voltage of hybrid STATCOM is found minimum which implies that the overall system cost will be reduced drastically.

Acknowledgment

I would like to express my whole hearted thankfulness to my guide Prof. Jayasree M. S. who guided me in selection of the project topic and for her sincere support. I also thank 'International Conference on Research Trends in Engineering, Science & Technology-2017', for providing an opportunity in presenting my thesis work.

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