International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 8, October - 2012

Size Selection Of Energy Storing Elements For A Cascade Multilevel Inverter STATCOM

Dr. Jagdish Kumar, PEC University of Technology, Chandigarh

Abstract— the proper selection of values of energy storing elements i.e. dc capacitor and coupling inductor is very important as far as its transient behavior, quality of reactive power injected to the system and of course, cost of the system i.e. STATCOM depend very much on the size of these parameters. In this research paper, an 11-level cascade multilevel inverter based STATCOM is simulated in MATLAB/SIMULINK environment and the effect of size of these passive parameters has been studied thoroughly on the performance of STATCOM for its transient and steady-state behavior where different aspects considered for the study are system dynamic response, THD contents in the output voltage and current of STATCOM, working range of STATCOM operation (variation of modulation index), DC voltage ripples, transient voltage overshoot etc. Both indirect as well as direct control schemes have been implemented for the purpose of above studies on an 11-level cascade multilevel inverter based STATCOM through digital simulation. A comprehensive result has been presented for wide range variations of these parameters. It has been found that the proper selection of these parameters has great impact on the performance of STATCOM for power systems applications. Further, it is notices that there are certain contradicting factors in choosing the proper values of these parameters.

***Index Terms*— CMLI STATCOM, coupling inductor, dc capacitor, THD, switching angles, control schemes**

I. Introduction

For fast voltage regulation of power systems, static synchronous compensator (STATCOM) is superior over existing var compensating devices due to its fast operation and independency of system voltage in reactive power supply as described in literature [1-2]. Basically three different types of STATCOM topologies have been reported in the literature depending on the type of voltage source inverter (VSI) used. These topologies can be classified as: i) PWM, ii) multi-pulse and iii) multilevel type [3-6]. Because of various disadvantages of PWM inverters such as high *dv/dt* per switching, low efficiency, high electromagnetic interference etc. [5], for high power applications, either multi-pulse or multi-level inverters are used. Presently multi-pulse inverters are not considered suitable for STATCOM applications because of requirement of zigzag transformer for interconnection of basic six-pulse inverter units making overall system complex and large space requirement; therefore, it is not economical [6-7]. In a multi-level inverter, the desired output voltage is synthesized from several levels of input dc voltages. By connecting sufficient number of dc levels, a nearly sinusoidal fundamental frequency voltage of high magnitude can be produced at the output of a multi-level inverter. The multi-level topology is further classified as: diode clamped type, flying capacitors type and cascade or isolated series H-bridges type. Due to modular configuration and least number of component requirements among all multilevel topologies, cascade multi-level inverter (CMLI) is considered to be the most suitable topology for power system applications [7-9]. Consequently, applications of CMLI based STATCOM for reactive power compensation in power systems has been studied in the literature [10-11] in order to improve the voltage profile. This compensation is achieved by STATCOM by generating or absorbing reactive power at the point where voltage needs to be controlled, known as point of common coupling (PCC), without the need of large external reactors or capacitors.

The performance and reliability of STATCOM depends very much on the values of passive components (dc capacitors and coupling reactor) chosen. In this article, extensive simulation studies have been carried in order to get optimal values of these reactive components (dc capacitors and coupling inductors) [10]. For selection of appropriate size of these parameters, different factors considered for simulation studies are: dc voltage ripples, transient voltage overshoot, system dynamic response, THD content in output voltage and current, variation in modulation index etc.

II. Static Synchronous Compensator

A. Basic Operating Principle

A STATCOM is basically a shunt connected voltage source inverter (VSI) which is connected to the power system bus through a coupling transformer or inductor (L_C). The voltage difference between the STATCOM output voltage (v_c) and the power system bus voltage (v_l) decides reactive power injection or absorption to the system [1]. This voltage difference can be achieved by two different methods: either by changing the modulation index (m) at constant dc link voltage (v_{dc}) (direct control) or by varying v_{dc} at fixed switching angles i.e. at constant m (indirect control) [2]. In indirect control, variation of v_{dc} is achieved by phase shifting v_c with respect to v_l.

B. Cascade Multilevel Inverter

The CMLI consists of a number of H-bridge inverter units with separate dc source for each unit and is connected in cascade or series. Each H-bridge can produce three different voltage levels: $+V_{dc}$, 0, and $-V_{dc}$ by connecting the dc source to ac output side by different combinations of the four switches S_1, S_2, S_3, and S_4 as shown in Fig. 1 and corresponding output voltage produced is shown in Fig. 2. In

Fig. 2, V_{ac} is output ac voltage and α is switching angle. The ac output of each H-bridge is connected in series such that the synthesized output voltage waveform is the sum of all of the individual H-bridge outputs [4, 7-9].

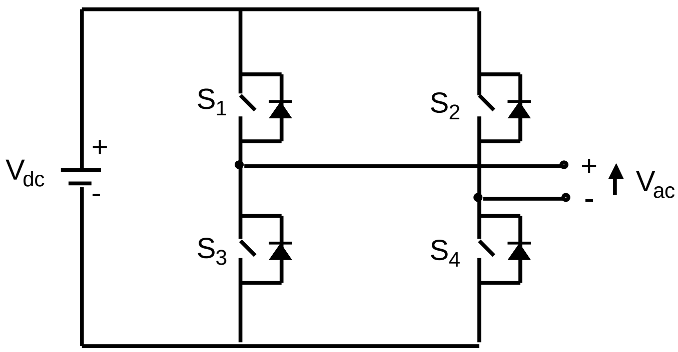

Fig. 1. An H-bridge of cascade multilevel inverter.

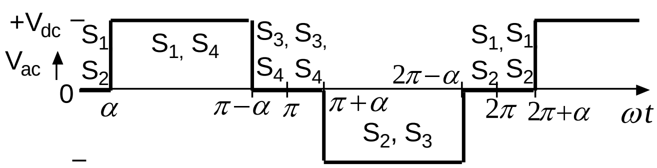

Fig. 2. AC output voltage of a single H-bridge.

By connecting sufficient number of H-bridges in cascade and using proper modulation scheme, a nearly sinusoidal output voltage waveform can be synthesized. The number of levels in the output phase voltage is 2*s*+1, where *s* is the number of H-bridges used per phase. In this work, an 11-level CMLI has been considered. In 11-level CMLI there are five H-bridges and corresponding firing angles are α_1, α_2, α_3, and α_4 and α_5. As the harmonic content of the output voltage depends on the angles $\alpha_1 \ldots \alpha_5$, these angles need to be chosen properly so that the output voltage waveform is nearly sinusoidal. In this work, the switching angles have been calculated by minimizing the aggregate contribution of all harmonic components up to 49^{th} order [11] which is represented by the index THD_{49} as shown in eqn. (1) below.

$$THD_{49} = \frac{\sqrt{V_5^2 + V_7^2 + \ldots + V_{49}^2}}{V_1} \times 100 \quad (1)$$

In eqn. (1), V_1, V_5, V_7, and V_{49} are magnitudes of the fundamental, fifth, seventh and forty ninth harmonic components respectively [11].

The performance of STATCOM for different values of passive parameters has been carried out through digital simulation study of the simple system shown in Fig. 3. The simulation studies have been carried out in the MATLAB/SIMULINK [12] environment.

The single-line diagram of the system under study is shown in Fig. 3.1, where it is assumed that a substation is feeding power to an inductive load through a distribution feeder. It is to be noted that in Fig. 3.1, different symbols used are as follows: R_S and L_S are series resistance and inductance of the distribution feeder, R_C and L_C are resistance and inductance of coupling reactor, R_L and L_L are the equivalent resistance and inductance of the load and the resistance R_P represents the switching loss of the CMLI. Although, in CMLI structure, each H-bridge has its own DC capacitor (C), but here an equivalent value of the capacitors has been considered and it has been shown as C_{eq}.

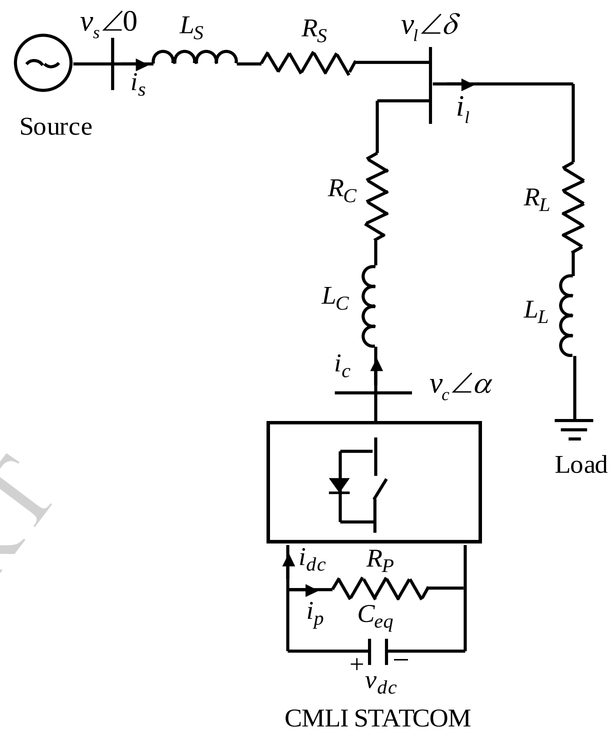

Fig. 3. Single-line diagram of CMLI based STATCOM.

III. SELECTION CRITERION FOR APPROPRIATE SIZE OF THE DC CAPACITOR

The DC capacitor is an important part of the CMLI STATCOM for reactive power compensation, because it is used as a circulating energy buffer as shown in Fig. 4. The size of the DC capacitor required in the STATCOM applications is much less than that of the ac capacitor bank for the static var compensator (SVC) of the same rating.

In an H-bridge inverter, the value of the required capacitance (C) can be expressed as follows [7]:

$$C = \frac{\sqrt{2} I (1 - \sin \alpha)}{2 \omega \varepsilon v_{dc}} \quad (2)$$

In equation (2), α is the value of the switching angle for an H-bridge of a CMLI, I is the current rating of the CMLI, ω is the angular frequency (radians/sec) and ε is the voltage ripple factor of dc voltage, i.e. $\varepsilon = (V_{dcmax} - V_{dcmin}) / (2v_{dc})$, whose value may varies from 5 - 20% for practical application. The switching angles are different for each H-bridge of a CMLI. Moreover, for a particular H-bridge, the switching angles are also different at different modulation indices. Hence, to calculate the required capacitance using equation (2), minimum value of the switching angle under all conditions should be chosen so that the DC voltage ripple will not be larger than the given regulation factor for all loads. Following factors have been considered for the selection of appropriate size of the dc capacitor:

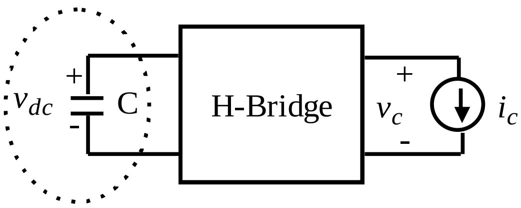

Fig. 4. DC capacitor utilized in an H-bridge of CMLI.

A. DC Capacitance v/s Voltage Ripples

In reactive power applications, the output voltage and current of the power inverters are almost 90 degrees out of phase; therefore, very small amount of real energy is exchanged in the capacitor. As a result, the size of the capacitor determines the amplitude of the voltage ripple across its dc link.

It can be observed from equation (2) that the voltage-ripple magnitude is indirectly proportional to the value of dc capacitor, i.e., for a given dc voltage (v_{dc}), the required capacitor size would be lesser for higher value of voltage ripples. For different values of the dc capacitor, voltage ripples have been observed for a given dc voltage across the dc capacitor as shown in Fig. 5 for an 11-level CMLI based STATCOM supplying reactive power to the ac system at 13.8 kV.

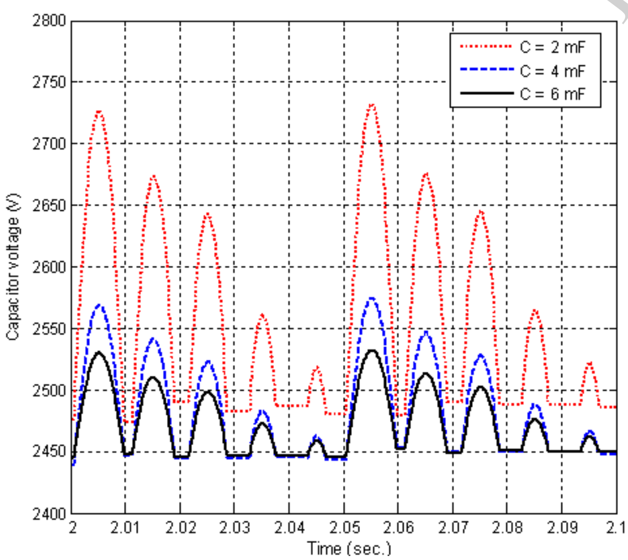

Fig. 5. Voltage ripples for different values of dc capacitance for v_{dc} = 2500 V for m = 0.8.

B. DC Capacitance v/s Modulation Indices

For a given load, the STATCOM is required to generate a fixed amount of reactive power at a constant voltage. It is known that the output ac voltage of the STATCOM depends on the product of the voltage across the dc capacitors and modulation index (m) as given by equation (3). In equation (3), V_1 is fundamental value of ac voltage and k = 20/π. Therefore, if modulation index is varied, the corresponding dc voltage across the capacitors will vary inversely i.e. for operation of the STATCOM at higher modulation index needs less value of dc voltage across the capacitors. It can be seen from the equation (2) that for a given value of dc capacitor, voltage ripples will be more at reduced value of v_{dc}. Hence at higher modulation indices, there will be more dc voltage ripples. The corresponding simulation result is shown in Fig. 6. The percentage voltage ripple factors calculated at modulation indices 0.70, 0.80, 0.90 are 1.84%, 3.06%, 3.80% respectively, verifying the above statement. Therefore, in order to keep the voltage ripples below a particular level, higher values of dc capacitors are needed at high modulation index.

$$V_1 = kmV_{dc} \quad (3)$$

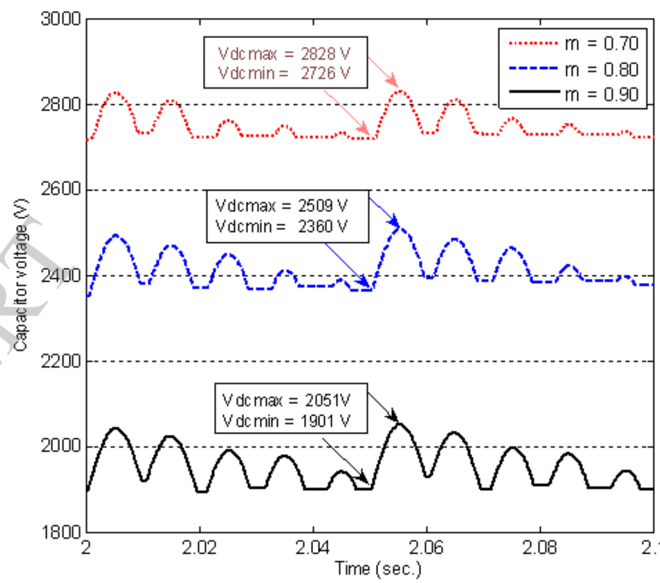

Fig. 6. DC voltage ripples across capacitor for different values of modulation indices at C = 4 mF.

C. DC Capacitance v/s Transient Voltage Overshoots

The variations of v_{dc} for three different values of dc capacitance for a step change in the STATCOM output current is shown in Fig. 7. From this figure it can be seen that the voltage overshoot increases with reduction in the value of dc capacitance. It is due to the fact that the time constant of smaller capacitor is less, and thus it charges faster than that of a large sized capacitor.

D. DC Capacitance v/s System Dynamic Response

In Fig. 8, time domain variation of the ac system voltage is shown when an inductive load is suddenly connected to the ac system for different values of the dc capacitance. As observed from this figure, the ac system voltage is brought back more quickly to the desired level with a smaller capacitance value without any appreciable enhancement in the peak overshoot. This is due to the fact that the smaller capacitor allows fast voltage change as compared to the larger one due to its smaller time constant.

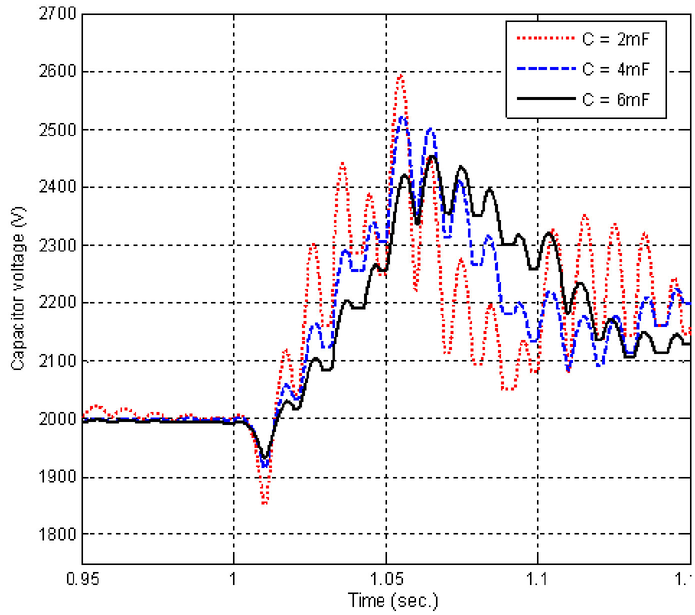

Fig. 7. DC voltage across the capacitors under a step change in the STATCOM output current.

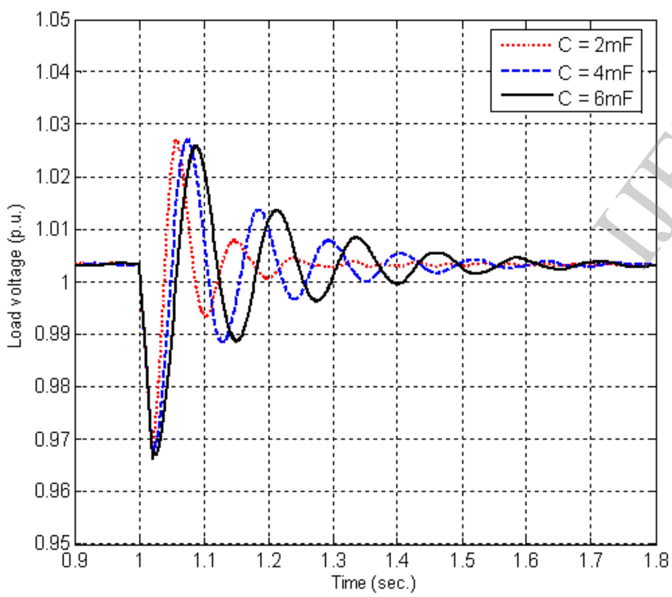

Fig. 8. Load voltage variations when a step load change occurs.

E. DC Capacitance v/s Harmonic Distortion in the STATCOM Voltage and Current

This is one of the important factors to be studied for evaluating the performance of the STATCOM. The total harmonic distortions (THD) in the output voltage and current of the STATCOM supplying reactive power to the ac system for different values of the dc capacitors have been studied and the results are shown in Fig. 9. It can be seen from Fig. 9 that the voltage THD is almost constant. Moreover, it is little for small values of the DC capacitor. Now, earlier it was shown that there are more voltage ripples for smaller values of DC capacitor. Hence, interestingly it indicates that voltage ripples help in reduction of voltage THD.

The variation of the output current THD of the STATCOM shows that the current harmonic distortions at lower value of dc capacitor are more as compared to those at higher values of dc capacitance.

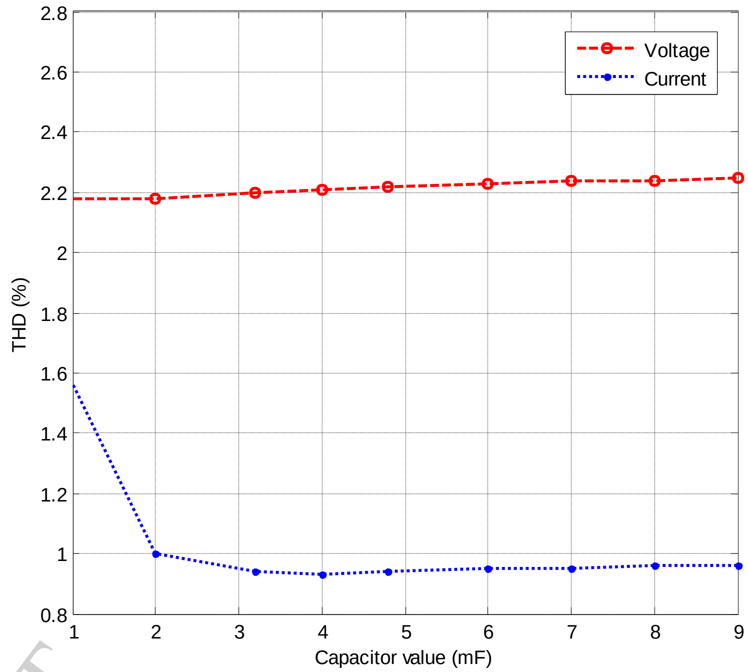

Fig. 9. The variations of harmonic distortion in the output voltage and current of the STATCOM as a function of DC capacitor at *m* = 0.9240.

For a given output current and operating voltage, the size of the dc capacitor required for a CMLI based STATCOM should be selected by considering following factors. The factors which limit the minimum capacitance are voltage ripples, transient voltage over shoot and current THD (high for very low value of dc capacitor). In contrast, the operation at higher modulation index requires higher dc capacitor and also the consideration of cost limits the use of a larger size of capacitor. The output voltage and current THD do not significantly improve with larger dc capacitor.

IV. Selection Criterion For Coupling Inductor

The coupling inductor is the second key component which determines the performance of the STATCOM. The connection of the coupling inductor to the ac system is shown in Fig. 10. It basically serves as a low-pass filter for the power electronic inverter.

The following key parameters which are affected by the variations in the value of coupling inductance are studied for a cascade multilevel inverter based STATCOM.

A. Coupling Inductor v/s THD of the STATCOM Output Current

As one of its two main functions, the coupling inductor in the STATCOM is used to filter out the harmonic components from the STATCOM output current. The harmonic components are primarily generated by the power frequency pulsating voltage synthesized by the high power inverter. It is known that a larger inductor attenuate more harmonic components from the output current. The variations of THD of the STATCOM output current as a function of the coupling inductor when the STATCOM is operating in the capacitance region is shown in Fig. 11. As can be seen, the output current THD decreases by appreciable amount with increasing the value of the coupling inductor. For example, in a typical case, the THDs for the inductor values of 10 mH and 20mH are 3.39% and 2.20% respectively. Thus, a larger coupling inductor improves the quality of the output currents of the inverter.

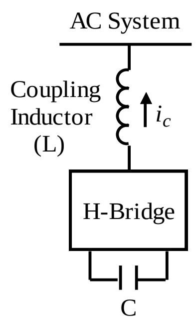

Fig. 10. Coupling inductor used in STATCOM applications.

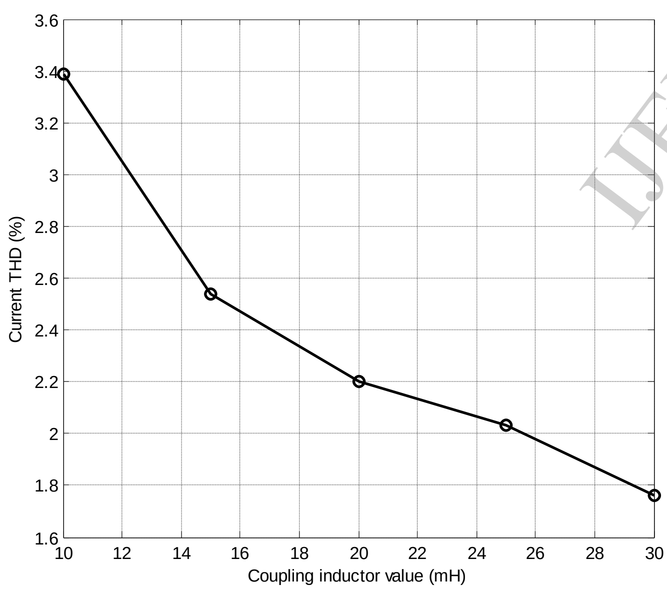

Fig. 11. Variation of the STATCOM output current THD as a function of coupling inductor.

B. *Coupling Inductor v/s System Dynamic Response*

The variations of ac system voltage (load voltage) and STATCOM current for different values of coupling inductor are shown in Figs. 12(a) and (b) respectively. These plots reveal that for a larger value of coupling inductor, the system dynamic response is slow as compared to the response with low value of the coupling inductor. It may also be observed from Fig. 12(b) that for a large value of inductor, current settles slowly.

C. *Coupling Inductor v/s Modulation Index*

For a given value of reactive power generation i.e. for a fixed amount of reactive current to be supplied to the ac system, higher coupling inductor needs more output voltage of the STATCOM. In case of operation with direct control scheme, the output voltage is increased by operating the STATCOM at higher modulation index as shown in the Fig. 12(c). Hence, the modulation index is proportional to the value of the coupling inductor. For inverter type II operation, output voltage is increased by increasing the dc capacitor voltage keeping modulation index constant, therefore there is no effect of the inductor value on the modulation index.

In conclusion, for a given output current and operating voltage, the minimum size of the coupling inductor is decided by output-current harmonic distortions. The maximum inductance is limited by the operating range of the inverter and, of course, by the cost.

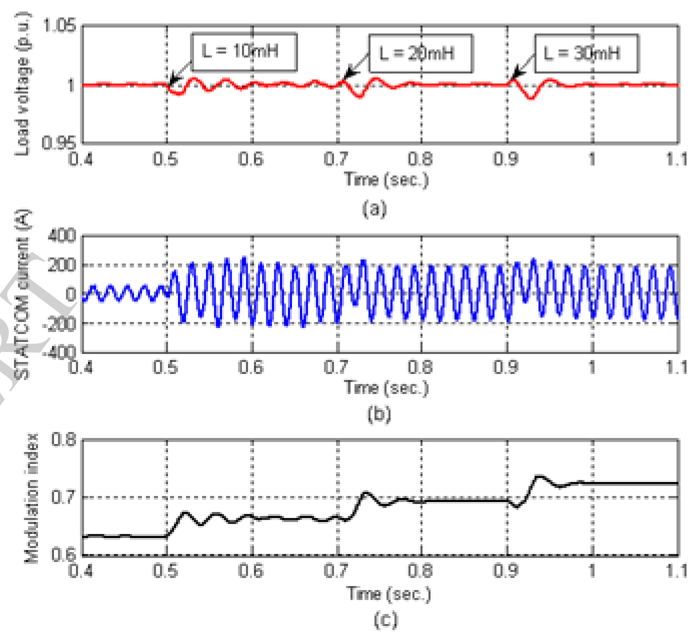

Fig. 12. Effect of varying coupling inductor on (a) ac system dynamic response, (b) dynamic response of the STATCOM output current and (c) variation of modulation index.

V. Conclusion

The passive elements used in CMLI based STATCOM dictate the performance of it for the reactive power applications and voltage regulation.. The different selections criterion for the two key components i.e. dc capacitor and coupling inductor have been investigated through time-domain simulation under various operating conditions. The limit on minimum value of dc capacitor is restricted by voltage ripples, transient voltage over shoot and current THD. The operation at higher modulation index requires higher dc capacitor. Cost is also limiting factor for higher value of dc capacitor. For a given output current and operating voltage, the minimum size of the coupling inductor is decided by output-current harmonic distortions. The maximum inductance is limited by the operating range of the inverter and the cost.

ISSN: 2278-0181
Vol. 1 Issue 8, October - 2012

REFERENCES

[1] L. Gyugi, "Dynamic Compensation of AC transmission Lines by Solid-State Synchronous Voltage Source", IEEE Transaction on Power Delivery, vol. 9, no. 2, pp. 904-911, April 1994.

[2] C. Schauder and H. Mehta, "Vector analysis and control of advanced static VAR compensators", Proc. Inst. Elect. Eng., vol. 140, no. 4, pp. 299–306, July 1993.

[3] Ben-Sheng Chen, Yuan-Yih Hsu, "An Analytical Approach to Harmonic Analysis and Controller Design of a STATCOM", IEEE Transaction on Power Delivery, vol. 22, no. 1, pp. 423-432, Jan. 2007.

[4] Amit Jain, Karan Joshi, Aman Behal, and Ned Mohan, "Voltage Regulation with STATCOMs: Modeling, Control and Results", IEEE Transaction on Power Delivery, vol. 21, no. 2, pp. 726-735, April 2006.

[5] L. M. Tolbert, F. Z. Peng and T.G. Habetler, "Multilevel converters for large electric drives", IEEE Transactions on Industry Applications, vol. 35, no. 1, pp. 36-44, Jan. /Feb. 1999.

[6] Pranesh Rao, and M.L. Crow, " STATCOM Control for Power System Voltage Control Applications", IEEE Transaction on Power Delivery, vol. 15, no. 4, pp. 1311-1317, October 2000.

[7] Fang Zheng Peng et al., "A Multilevel Voltage-Source Inverter with Separate DC Sources for Static Var Generation", IEEE Trans. on Industry Applications, vol. 32, no. 5, pp. 1130-1138, September/October 1996.

[8] Diego Soto, and Ruben Pena, "Nonlinear Control Strategies for Cascaded Multilevel STATCOMs", IEEE Transactions on Power Delivery, vol. 19, no. 4, October 2004.

[9] Qiang Song, Wenhua Liu, and Zhichang Yuan, "Multilevel Optimal Modulation and Dynamic Control Strategies for STATCOMs Using Cascade Multilevel Inverters", IEEE Transaction on Power Delivery, vol. 22, no. 3, pp. 1937-1946, July 2007.

[10] S. Dong, W. Zhonghong, J. Y. Chen and Y. H. Song, "Harmonic Resonance Phenomena in STATCOM and Relationship to Parameters Selection of Passive Components", IEEE Transactions on Power Delivery, vol. 16, no. 1, pp. 46-52, January 2001.

[11] Jagdish Kumar, Biswarup Das and Pramod Agarwal, "Optimized Switching Scheme of a Cascade Multilevel Inverter", *Electric Power Components and Systems, vol. 38, issue 4, pp. 445-464, January 2010*.

[12] MATLAB/SIMULINK Power System Block Set v7. The Math Works, 2006.