PERFORMANCE EVALUATION OF CONTROL STRATEGIES FOR CMLI BASED STATCOM IN VOLTAGE REGULATION

Dr. Jagdish Kumar

Department of Electrical Engineering, PEC University of Technology, Chandigarh

Abstract:—In this article, performances of two control strategies are evaluated for cascade multilevel inverter based STATCOM for reactive power compensation and power system bus voltage regulation. In direct control scheme modulation index (switching angles) is varied at constant dc capacitor voltage in order to vary the output voltage of STATCOM while in case of indirect control scheme the dc capacitor voltage is varied at constant modulation index. Due to variation in modulation index, THD produced in output voltage varies while at constant modulation index THD can be kept at minimum level. On the other hand, output voltage variation is slow in case of indirect control scheme due to slow variation in dc capacitor voltage. The above facts have been verified by using digital simulation in MATLAB/SIMULINK environment on an 11-level cascade multilevel inverter based STATCOM under variations of load. The simulated results have been validated through experimental results on 11-level cascade multilevel inverter based STATCOM and it has been found that experimental results are in close agreement with simulated results.

Keywords:—cascade multilevel inverter, dc capacitor voltage, direct control scheme, indirect control scheme, modulation index, total harmonic distortion.

I. INTRODUCTION

Voltage control in an electric power system is an important requirement for proper operation of electric power equipment to prevent damage such as overheating of generators and motors, to reduce transmission losses and to maintain the ability of the system to withstand disturbances and prevent voltage collapse. One of the major causes for voltage disturbances in power systems is reactive power drawn/supplied by various components of power systems, such as inductors, condensers, non-linear loads, power electronic converters etc., therefore, the control of reactive power in the power system must be regulated/compensated properly [1-2].

The reactive power in the system can be compensated by using conventional methods such as fixed capacitors, inductors, synchronous condensers etc or using power electronic switches based compensators such as TSC, TCR etc. [2-4] The above mentioned reactive power compensating devices are having disadvantages like less accuracy of compensation, slow response, less flexibility, more cost, operating dependency on system voltage etc.

In the last couple of years, commercial availability of power electronics based switches with high power handling capacity such as GTO thyristors, IGBTs etc. have led to the development of power electronic converters. A second generation FACTS device, using key component as voltage source inverter (VSI), has made significant impact in the field of reactive power compensation, and is known as static synchronous compensator (STATCOM). The STATCOM almost overcomes all the issues related with reactive power compensation and voltage regulation. One of the important merits of the STATCOM is that its operation does not depend on power system voltage [4]. For proper reactive power exchange with power system, the STATCOM output voltage needs to be controlled efficiently, and accordingly, two control schemes i.e. direct and indirect control strategies are used. Each of these control strategies has their merits and demerits in sense of response time, harmonic distortion in output voltage etc [5].

II. STATIC SYNCHRONOUS COMPENSATOR

A. Basics

The basic STATCOM model consists of a voltage source inverter, dc side capacitors (C) with voltage V_{dc} on each capacitor, and a coupling reactor (L_C) or a transformer. The ac voltage difference across the coupling reactor produces reactive power exchange between the STATCOM and the power systems at the point of common coupling (PCC). If the output voltage of the STATCOM (V_C) is more than the system voltage (V_L) then reactive power is supplied to the power system and reverse happen if V_C is less than that of V_L. The output voltage of the STATCOM can be controlled in two ways either by changing the switching angles while maintaining the dc capacitor voltage at a constant level (inverter type I control/direct control) or by changing dc capacitor voltage at fixed switching angles (inverter type II/indirect control) [5]-[6]. The charging and discharging of dc capacitor voltage is accomplished by phase shifting of STATCOM voltage with respect to power system voltage. Advantage of type II control over type I is that, the switching angles can be selected in such a way that harmonic distortions in V_C can be kept at minimum level, thereby injecting harmonics in the power system [5]; but its response time is slow as compared to the type I inverter control. The configuration of the STATCOM is shown in Fig. 1.
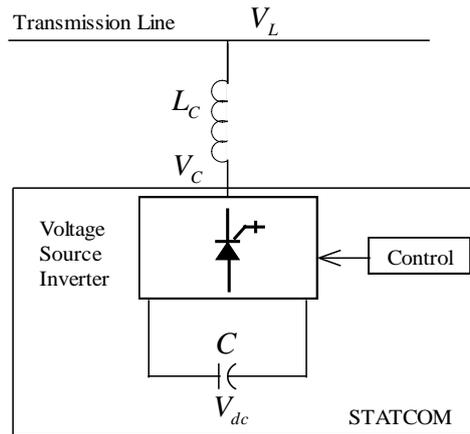
Fig. 1. STATCOM configuration.

From topology point of view, the STATCOM can be classified into two categories: i) multi-pulse type and ii) multilevel type. In multi-pulse inverter topology, six-pulse inverter units are connected through a specially designed zigzag transformer to achieve high pulse inverter (i.e. 12, 24, 48-pulse) for better waveform and high power applications. The necessity of zigzag transformer which occupies more space and makes the configuration more complex is major demerit of it [7-8]. The alternative topology of STATCOM is based on multilevel inverters. The multilevel inverters are further classified as: diode-clamped type, flying capacitors type and cascade or isolated series H-bridges type. The different multilevel inverter topologies have their own merits and demerits depending on the number of components requirement, applications, configuration, cost, space requirement, modularity etc. Cascade multilevel inverter (CMLI) is considered most suitable topology for STATCOM for power systems voltage regulation applications [8-12].

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. In Fig. 2 (a) two H-bridges (H_1 and H_2) are connected in cascade or series producing output voltage as shown in Fig. 2 (b). 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. 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 [9-12].

(a)   (b)
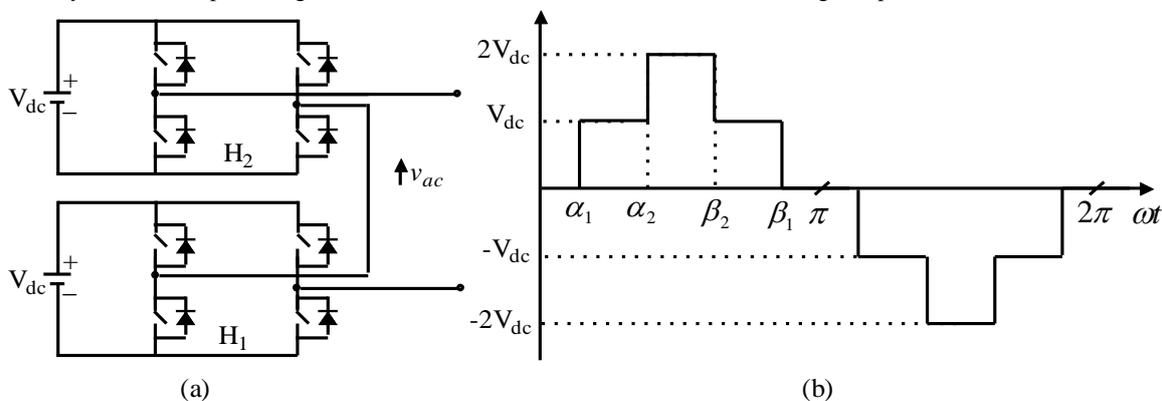
Fig. 2. Configuration of single-phase five level cascade multilevel inverter.

By connecting the 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 $2s+1$, where s is the number of H-bridges used per phase. The Fig. 2 (b) shows five-level output phase voltage waveform using two H-bridges. The switching angles α_1 and α_2 are corresponding to H_1 and H_2 respectively while $\beta_1 = \pi-\alpha_1$ and $\beta_2 = \pi-\alpha_2$. In case of 11-level CMLI five H-bridges per phase are required and the magnitude of the ac output phase voltage is given by sum of output voltages due to each H-bridge.

C. Switching Angle Selection

To synthesize multilevel ac output voltage using different levels of dc inputs, the semiconductor devices must be switched on and off in such a way that desired fundamental voltage obtained is nearly sinusoidal i.e. having minimum harmonic distortions. Different switching techniques are available for computing switching angles for the semiconductor devices [13]. Generally, the fundamental frequency switching scheme is considered more suitable for power system applications. In fundamental frequency switching scheme the devices are turned on and off once in a cycle, thereby producing less switching losses. Generally, the switching angles at fundamental frequency are computed by solving a set of nonlinear equations known as selective harmonic elimination (SHE) equations such that certain order harmonic components

(generally lower order) are eliminated [12-16]. Alternatively, the switching angles can be calculated by using some optimization based technique so that total harmonic distortion (THD) up to certain order (generally up to 49th order) is minimized instead of eliminating some individual harmonic components [17]. The details of switching angles calculation is given in [17]. In this work, the switching angles calculated using optimization based technique [17] which minimization overall THD is used.

III. CONTROL STRATEGIES FOR CMLI BASED STATCOM

For proper regulation of the ac system voltage, the output voltage generated by the cascade multilevel inverter needs to be varied smoothly and continuously so that the right amount of the reactive power can be exchanged with the ac system at all instants, therefore, an efficient control system is required. In this paper both direct and indirect control schemes have been implemented for this purpose [5-6], [18].

A. Direct Control Scheme

In case of direct control scheme, the output voltage is varied by varying the modulation index (m) i.e. by varying the switching angles of individual H-bridges of CMLI while keeping the dc capacitors voltages constant. The direct control scheme employed in this work is shown schematically in Fig. 3 for a CMLI having in general s number of H-bridges (for 11-level CMLI, s = 5). In general, the switching angles corresponding to each value of 'm' for each H-bridge are calculated off-line and are stored in a look-up table.

In Fig. 3, the reference ac system voltage (V_{L_ref}) is compared with the actual voltage V_L of the ac system and corresponding error (i.e. the difference between these two) is processed through a PI controller (Controller 1) which produces an appropriate value of modulation index (m) needed for maintaining the ac system voltage at the desired level. Subsequently, the switching angles corresponding to the given m are obtained from the look-up table. In order to keep the dc capacitor voltages constant, a small amount of active power flow is made possible by phase shifting (lagging) the STATCOM voltage with respect to the ac system voltage by a small angle (φ), termed as load angle. The load angle is calculated by another PI controller (Controller 2) according to the difference between the reference capacitor voltage (V_{dc_ref}) and the actual capacitor voltage (V_{dc}). The switching angles obtained from the look-up table are modulated (delayed or advanced) by the load angle and finally, these modulated switching angles are used to generate the firing pulses to the semiconductor devices. Also, these modulated switching angles are swapped after each half cycle in order to balance the capacitor voltages [12].
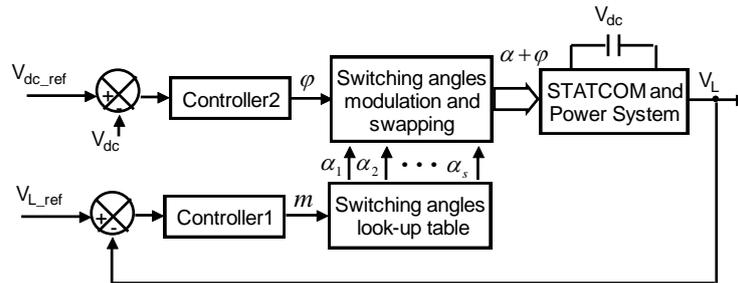
Fig. 3. Schematic diagram for direct control scheme of a STATCOM.

B. Indirect Control Scheme

`   In indirect control scheme the output voltage is controlled by varying the dc capacitor voltages at constant modulation index (i.e. at fixed switching angles). The indirect control scheme employed in this work is shown schematically in Fig. 4 for a CMLI having s number of H-bridges. As in direct control scheme, the switching angles for each H-bridge are calculated off-line and are stored in a look-up table. However, in this case, we can have fixed switching angles for a given value of m or if it is required to change m in that case we may have the look-up table.
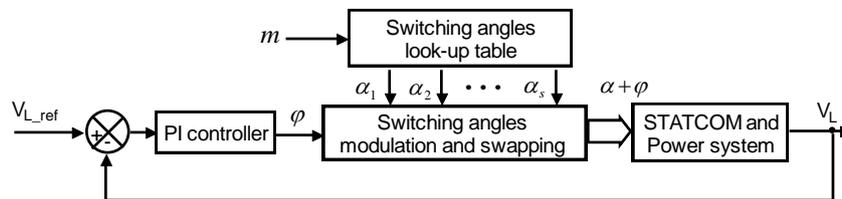
Fig. 4. Schematic diagram of indirect control scheme for STATCOM.

In Fig. 4, the reference ac system voltage (V_{L_ref}) is compared with the actual voltage V_L of the ac system and corresponding error (i.e. the difference between these two) is processed through a PI controller which produces a desired value of load angle by which the STATCOM voltage needs to be phase shifted (lagging/leading) with respect to the ac system voltage in order to charge/discharge the dc capacitors. The charging or discharging of the dc capacitors increase or decrease the output voltage of the STATCOM which eventually controls the ac system voltage by proper exchange of the reactive power. In this case also, the switching angles need to be modulated by the load angle and swapped for the same

reasons as discussed in the case of direct control scheme. It is to be noted that as compared to the direct control scheme, in indirect control scheme, only one controller is required.

IV.   DIGITAL SIMULATION RESULTS

For validating the performance of the control strategies discussed in Section III, digital simulation studies of the 11-level CMLI STATCOM have been carried out on MATLAB/SIMULINK [20] environment under different conditions of load variations. The single line diagram of system simulated in SIMULINK [20] for these studies is shown in Fig. 5 and the parameters used are given in appendix.

In Fig. 5, the different loads are connected through circuit breakers CB1, CB2 and CB3 for testing the performance of the STATCOM under sudden load change conditions. CB1 is closed at t = 0.0 s while STATCOM is connected to load bus with the help of circuit breaker CB4 at t = 0.2 s. Initially when STATCOM is not connected, load bus voltage is less than 1 pu because inductive Load 1 is connected, therefore, error signal is generated which either increase modulation index (direct control) or capacitor voltage (indirect control) due to controller action.
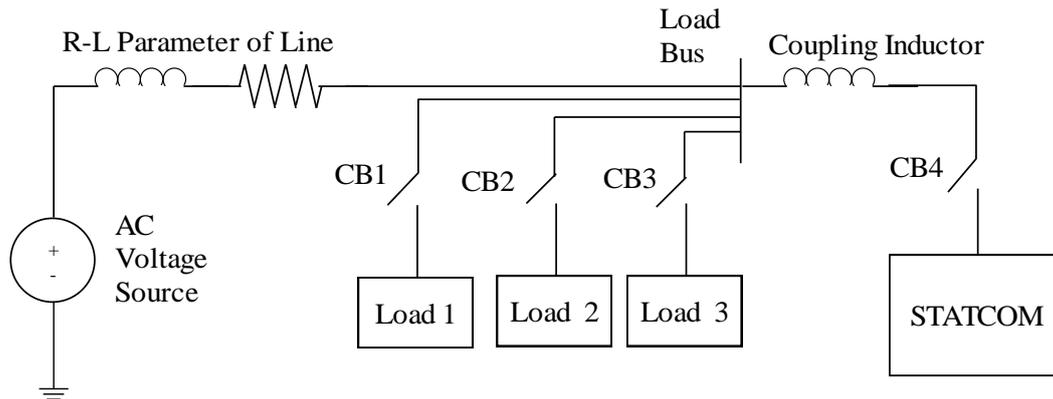
Fig. 5. Single line diagram of system simulated in MATLAB for study of STATCOM operation.

A.   Direct Control Scheme

The Direct control scheme as discussed in Section III (shown in Fig. 3) has been implemented for this study. The parameters of PI controllers are designed by using Zeigler-Nichols method [19]. For investigating the performance of the STATCOM with the designed control schemes under sudden load change conditions, sequence of events as mentioned in TABLE I has been followed in the simulation. The corresponding waveforms are shown in Figs. 6 (a)-(c).

TABLE I
Variations of different parameters of STATCOM and load bus voltage under load variations

Time (s)	Status of Circuit breakers				Load bus voltage	Total Load (pu)		Modulation index	STATCOM voltage	Net flow of reactive power	Dc Capacitor voltage
	CB1	CB2	CB3	CB4		P	Q				
0.0	closed	open	open	open	below 1 pu	0.2	0.4	increases	Not connected	No flow	precharged value
0.2	close	open	open	closed	rises and settles at 1 pu	0.2	0.4	drops from initial value	drops from initial value	from STATCOM to load bus	attains constant value
1.0	close	closed	open	close	falls and settles at 1 pu	0.6	1.0	increases	increases	from STATCOM to load bus	constant
2.0	close	close	closed	close	rises and settles at 1 pu	0.8	0.4	decreases	decreases	from STATCOM to load bus (less)	constant
3.0	close	opened	close	close	rises and settles at 1 pu	0.4	-0.2	decreases	decreases	from load bus to STATCOM	constant
4.0	close	open	opened	close	falls and settles at 1 pu	0.2	0.4	increases	increases	from STATCOM to load bus	constant

Fig. 7 depicts the three-phase load voltage variations at and around 3 sec. to show the transient behavior of the system voltage. It can be seen from Fig. 7 that three-phase voltages are well balanced and desired voltage level is attained within a power cycle i.e. it operation is very fast.
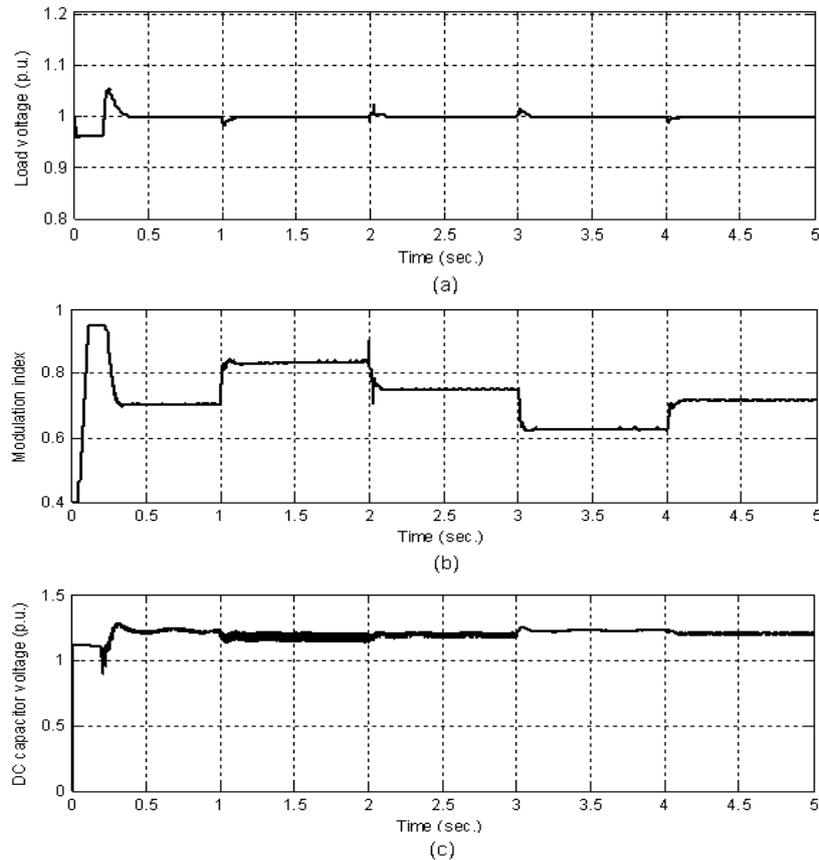
Fig. 6. Variations of (a) load voltage, (b) modulation index and (c) dc capacitor voltage (direct control).
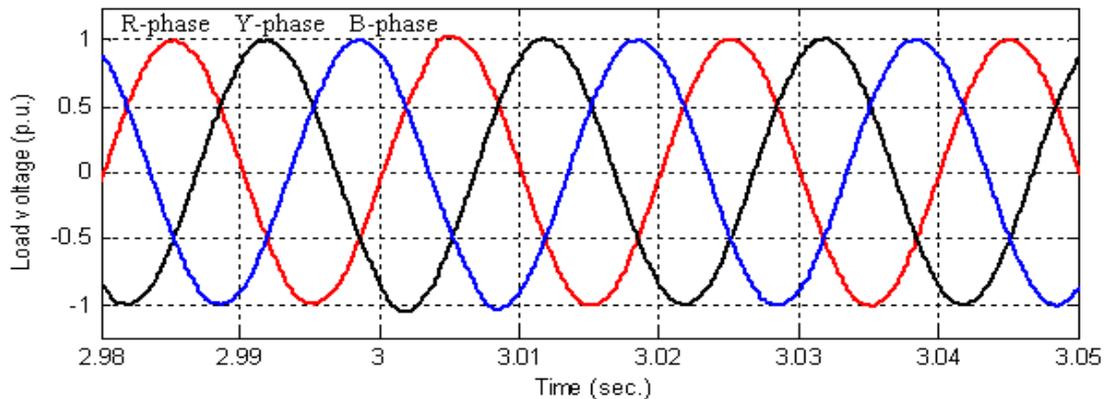
Fig. 7. Load voltage variation of three-phases at t = 3 sec. (direct control).

B. Indirect Control Scheme

The indirect control scheme as shown in Fig. 4 has been implemented and the parameters of PI controller are designed by following Z-N technique [19].

In order to compare the performances of two control strategies, the system is studied under similar sequence of load variations as discussed for direct control scheme. The corresponding waveforms are shown in Figs. 8 (a)-(c).

The sequence of events is similar to direct control scheme as given in TABLE I except that in place of modulation index, dc capacitor voltage will vary in similar manner at constant modulation index.

Fig. 9 depicts the three-phase load voltages variations at and around 3 sec. to show the transient behavior of the system voltages. It can be seen from Fig. 9 that three-phase voltages are well balanced and desired voltage level is attained within 2-3 power cycles as expected because of capacitors dynamics i.e. operation slow.
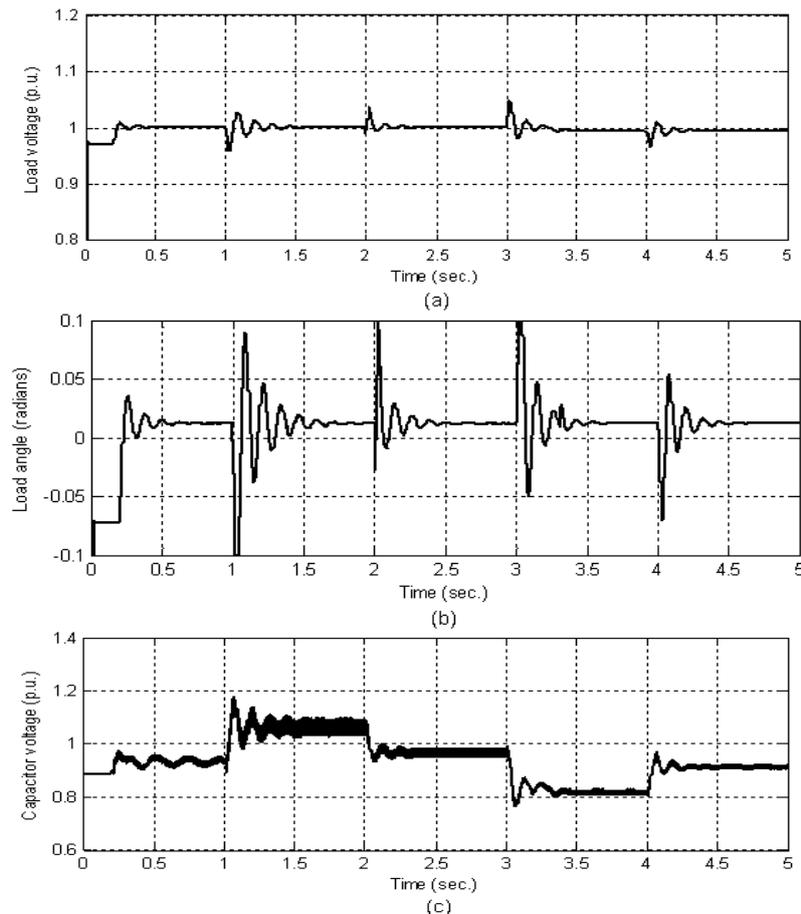
Fig. 8. Variations of (a) load voltage, (b) load angle and (c) dc capacitor voltage (indirect control).
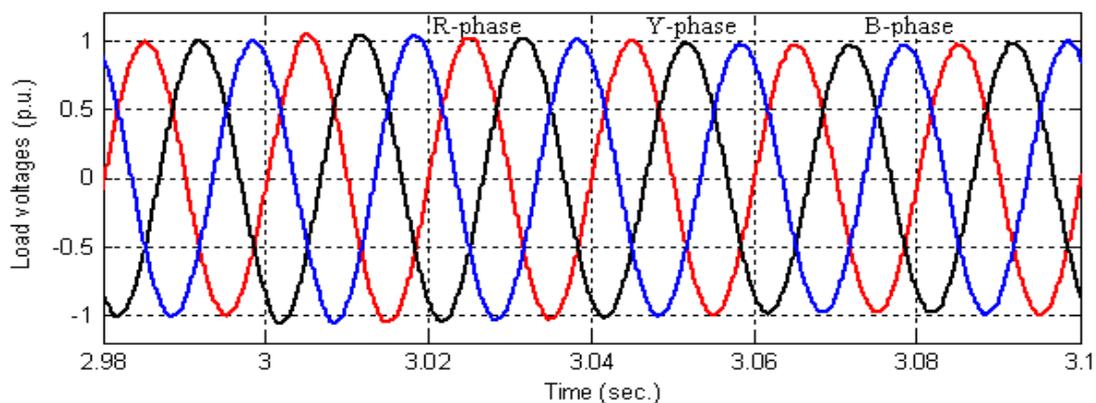
Fig. 9. Load voltage variations of three-phases at t = 3 sec. (indirect control).

C. Comparison of Direct and Indirect Control Schemes

The comparison of direct and indirect control schemes for a CMLI STATCOM is carried out based on above simulation studies. The comparison is based on mainly two factors i.e. the speed of the response and THD in the output voltage under identical system and load parameter variations.

Figs. 10 (a)-(b) show load voltage variation under the application of different sequences of loads as discussed in this section. These figures reveal that the speed of load voltage restoration is faster in case of directly controlled STATCOM. On account of faster speed, the enhancement or reduction in the load voltage on the application or removal of same loads is much less in direct control schemes as compared to those in indirect control scheme. As an illustration, Figs. 11 (a)-(b) show the variation of load voltage with both these control schemes when an inductive load is applied at t = 1 sec. From this figure, it can be seen that the load voltage is controlled much faster in the direct control as compared to indirect control scheme.
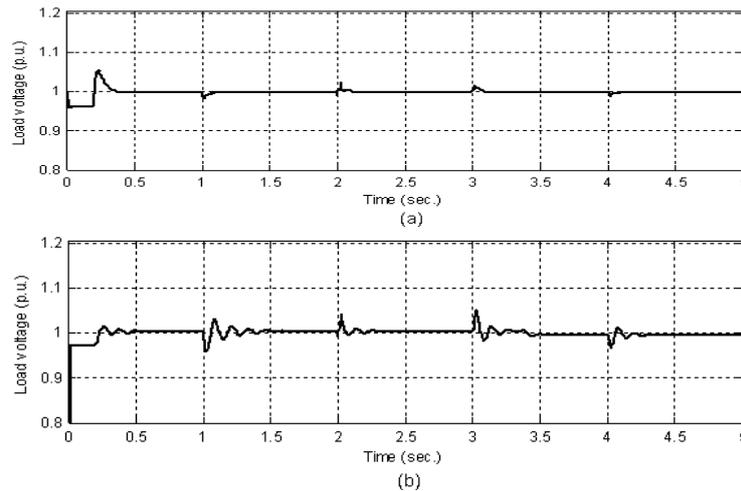
Fig. 10. Load voltage variation (a) direct control scheme and (b) indirect control scheme.
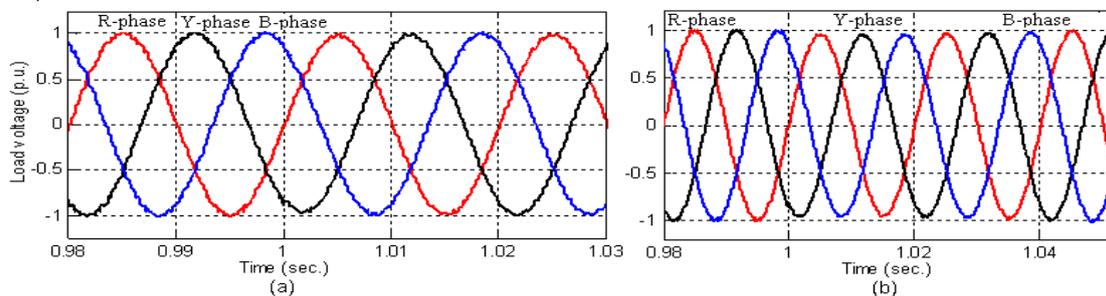
Fig. 11. Load voltage variation of three-phases at t = 1 sec. for (a) direct and (b) indirect control schemes.

THD in load voltage have also been determined using FFT analysis for both control schemes at different instants under load variation and these values of THD are given in TABLE II. It can be observed from this TABLE II that THD in load voltage at different instances of time is less in case of indirect control scheme as compared to direct control scheme irrespective of the nature of loads connected. This fact is due to change in THD level with modulation index in case of direct control scheme as compared to indirect control scheme where modulation index is kept constant [17].

TABLE II
Comparison of harmonic distortions in load voltage for direct and indirect controlled STATCOM

S. No.	Time (s)	THD in load voltage (%)	
		Direct control	Indirect control
1.	0.50	1.31	0.70
2.	1.50	0.93	0.74
3.	2.50	0.52	0.34
4.	3.50	0.59	0.33
5.	4.50	1.45	0.68

V. EXPERIMENTAL RESULTS

Prototype models of the DSP (*dSPACE*)-based three-phase 5-level and single-phase 11-level Cascade Multilevel Inverter based STATCOMs have been developed in the laboratory for experimental studies. The power circuit consists of 24-power devices which are used to make six H-bridges. These six H-bridges can be used for the synthesis of single-phase 11-level or three-phase five-level CMLI. Three coupling inductances are connected in series with the three lines on ac side of inverter and six dc capacitors are connected on the dc side of inverter. A DSP *DS1104* of dSPACE is used for the real-time simulation and implementation of control algorithm. The control algorithm is first designed in the MATLAB/Simulink [20] software. The Real-time workshop of MATLAB automatically generates the optimized C-code for real-time implementation. The interface between MATLAB/Simulink and Digital Signal Processor (DSP, *DS1104* of dSPACE) allows the control algorithm to be run on the hardware, which is an MPC8240 processor. The master bit I/O is used to generate the required 12 gate pulses and 8 analog to digital converters (ADCs) are used for acquiring the line currents, supply voltages and dc-bus capacitor voltages. Different parameters chosen for hardware implementation of CMLI based STATCOM are given in TABLE III.

TABLE III
Parameters for hardware implementation of CMLI based STATCOM

S. No.	Parameters	1-phase, 11-level	3-phase, 5-level
1.	System voltage	173 V (line-to-line)	125 V (line-to-line)
2.	Inductive load	1000 VA	500 VA
3.	Current rating	3.33 A	2.3 A
4.	Series inductance (L_S)	3.38 mH	3.38 mH
5.	Coupling inductance (L_C)	16.85 mH	16.85 mH
6.	DC capacitance for each H-bridge	1000 μF	1000 μF
7.	Modulation index (indirect control)	0.9240	0.9240
8.	Modulation index (direct control)	0.7000 (m_{max} = 0.95)	0.7000 (m_{max} = 0.95)
9.	DC capacitor voltage	45 V (m = 0.7000)	80 V (m = 0.7000)
10.	Switching device	MOSFET (400 V, 10 A)	MOSFET (400 V, 10 A)

The performance of CMLI based STATCOM is to be investigated for load bus voltage regulation, a voltage sensor is used to measure the load voltage. The peak value of sensed load voltage is converted into an equivalent digital value using analog to digital converter (ADC) of dSPACE. The measured load bus voltage is compared with the reference value (desired value, V_{L_ref}) for error generation. The difference between these two values (error) is processed through a PI controller and the controller output varies the voltage generated by CMLI according to control schemes implemented in Section III.

A. Direct Control Scheme
Fig. 12 demonstrates the voltage control capability of CMLI based STATCOM through direct control. An inductive load is connected suddenly to the load bus and due to this bus voltage goes down, the moment STATCOM is connected, it is restored to its normal value quickly.
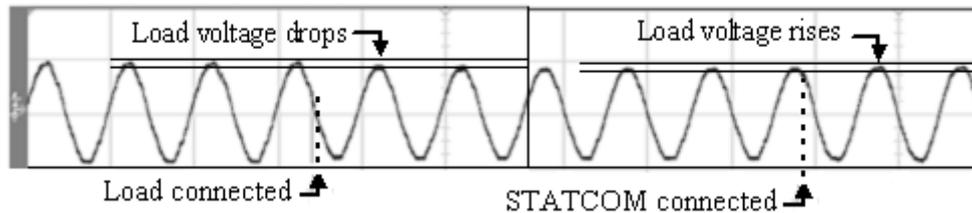
Time scale: 20msec. per div., Load voltage scale: 150 V per div.
Fig. 12. Variations of load voltage for 1-phase 11-level CMLI based STATCOM (direct control).

B. Indirect Control Scheme
Fig. 13 shows the voltage control capability of a STATCOM through indirect control scheme. Variation of load voltage is shown in Fig. 13 under sudden application of an inductive load, and subsequent connection of the STATCOM to the power system load bus. It can be seen from Fig. 13 that when an inductive load is connected, voltage of load bus drops. Due to reduction in load voltage from its reference value, an error signal is processed through a PI controller. The output of PI controller is basically the load angle by which STATCOM voltage is phase shifted (lagging, in case of inductive load) with respect to load voltage thereby enabling the capacitors to charge which in turn increases the STATCOM output voltage. The increased STATCOM voltage injects more reactive power to the power system, thereby bringing the load voltage back to its nominal value. In case when STATCOM is switched load voltage is restored to its normal value in 2-3 power cycles.

As discussed earlier, the voltage control capability of directly controlled STATCOM is faster than that of indirectly controlled STATCOM. Experimentally this fact can be observed from the results of Figs. 12 and 13 where in Fig. 12 load voltage attains 1 pu value in sub cycle time whereas in Fig. 13 it attains 1 pu in 2-3 cycle time.
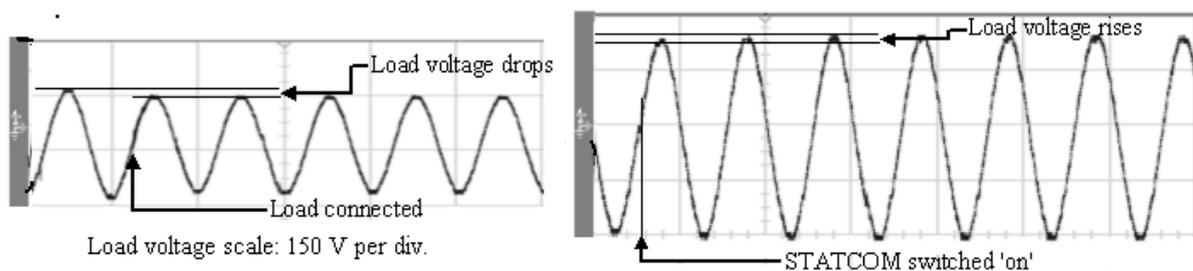
Time scale: 20 msec. per div.   Load voltage scale: 75 V per div.
Fig. 13. Variations of load voltage in 1-phase 11-level CMLI based STATCOM (indirect control).

VI.   CONCLUSION

The performance of CMLI based STATCOM for load voltage regulation in the power system has been studied using simulation and experimentally. Both control schemes for load voltage regulation i.e. direct as well as indirect control schemes have been implemented successfully. In case of direct control scheme fast voltage regulation of load voltage is achieved as compared to indirect control scheme. The experimental results corroborate the results obtained through MATLAB simulation.

APPENDIX

Parameters of the ±5MVAr, 13.8kV STATCOM and power system are given below:

Base voltage = 13.8 kV, Base power = 5MVA, v_s = 1.0,   Short Circuit Capacity = 10 (pu), ω = 314 rad./sec., X/R Ratio = 4, m_0 = 0.7000, R_S (series resistance) = 0.45Ω, L_S (series inductor) = 4.8 mH, R_C (resistance of coupling inductor) = 0.01 Ω, L_C (coupling inductor) = 28 mH, C = 4800 µF, v_{dcref} = 12500 V; Load 1 (P = 0.2 pu, Q = 0.4 pu), Load 2 (P = 0.4 pu, Q = 0.6 pu), Load 3 (P = 0.2 pu, Q = -0.6 pu (capacitive)), load voltage controller's (direct control) parameters: K_P = 5, K_I = 200; dc capacitor voltage controller's parameters : K_P = -3.15, K_I = -643, load voltage controller (indirect control) parameters: K_P = 3.5, K_I = 330, modulation index = 0.9240.

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