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Direct Voltage Control in Distribution System using CMLI Based STATCOM

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Abstract. This article presents a technique using system identification for the determination of transfer functions of a CMLI Static Synchronous Compensator used in power systems for the design of parameters of controllers in order to minimize voltage fluctuations and capacitor voltage balancing. The transfer functions obtained using system identification technique have been used for the determination of controllers' parameters for load bus voltage and capacitor charge balancing using Ziegler-Nichols technique. Digital simulation on an 11-level CMLI based Static Synchronous Compensator is carried out using MATLAB/SIMULINK for different load combinations using PI controllers' parameters as obtained corresponding to identified model. It is found that simulation results obtained using identified model give good performances.

Keywords: CMLI, STATCOM, system identification, modulation index.

1 Introduction

For fast voltage regulation of power systems, application of static synchronous compensator (STATCOM) and its superiority over static var compensator (SVC) are well established in the literature [1-4]. Basically three different types of STATCOM have been reported in the literature, namely, i) PWM, ii) multipulse and iii) multilevel [5-8]. Because of various disadvantages of PWM inverters like high rate of change of voltage per switching, poor efficiency, EMI etc. [7], for high power systems applications, generally, inverters based on multipulse or multilevel topology are used [8]. For transmission system voltage control, applications of multipulse inverter have been reported in [9]. Due to large size, high cost and complexity, the multipulse inverter based STATCOM is rarely used in distribution systems.

Contrary to multipulse inverter, a multilevel inverter produces the desired output voltage by synthesis of several levels of input dc voltages. A nearly sinusoidal fundamental frequency output voltage of high magnitude can be produced by connecting sufficient number of input dc levels. The different multi-level topologies available in literature are mainly: diode clamped multilevel inverter (DCMLI), flying capacitors multilevel inverter (FCMLI), and cascade multilevel inverter (CMLI) [8-10]. Among different multilevel topologies available, CMLI is considered most suitable for power systems applications due to its modular configuration and least number of components required [8, 10-11]. Mostly, the applications of CMLI based STATCOM in power systems have been studied for load reactive power compensation [12-14] and this does not guaranties for exact control of load bus voltage in the event of any disturbances in the power systems.

To address this issue, in this work, the application of CMLI based STATCOM for the control of load bus voltage in distribution systems is demonstrated. Basically, two control schemes (indirect and direct) exist in literature for load bus voltage control using STATCOM [4], the direct voltage control scheme has been chosen in this work. In a direct control scheme, two separate controllers are used; one for voltage control of the load bus and the other for regulation of the dc capacitor voltage. For proper design of these two controllers, accurate system models or transfer functions are necessary. However, it is very difficult to get an accurate model of a CMLI STATCOM due to difference in the dynamic properties and control capabilities of individual H-bridges, and also dc voltage variations cannot be neglected during the conduction period of H-bridges [15].

Above modeling difficulties have been overcome in this paper by using a system identification technique based on prediction error method (PEM) for determination of model of a CMLI based STATCOM. The performance of the identified models is compared with that of the fundamental frequency models, and it is found that the performance of identified models is superior. Based on the identified models, the design of two PI controllers is carried out using Ziegler-Nichols tuning method [16].

2 Static Synchronous Compensator

2.1 Basic Operating Principle

STATCOM is one of the important shunt FACTS devices used for voltage control and reactive power compensation in power system. It is basically a Voltage Source Inverter (VSI) connected to a power system bus through coupling transformer/inductor (let L_C) and a controller [17]. The voltage difference between the STATCOM output voltage (v_c) and the power system bus voltage (v_l) decides reactive power exchange between the STATCOM and power system bus (the reactive power flows from high voltage to low voltage) [1]. By varying the output voltage of a STATCOM, the reactive power injected into or absorbed from the power system bus can be varied thereby controlling the power system bus voltage. The output voltage of a STATCOM can be controlled by varying dc capacitor voltage (v_{dc}) at constant switching angles of H-bridges (indirect control) or by varying switching angles at constant dc capacitor voltage (direct control) [4], [17].

2.2 Cascade Multilevel Inverter

Cascade multilevel inverter consists of number of H-bridges inverter units having isolated dc source for each unit and are connected in series. Three voltage levels i.e. $+V_{dc}$, 0, and $-V_{dc}$ (V_{dc} is input dc voltage) are produced by proper switching of devices of each H-bridge [17-18]. The synthesized output voltage waveform is the sum of all of the individual H-bridge's outputs.

Nearly sinusoidal output voltage waveforms can be synthesized by using sufficient number of H-bridges in cascade and choosing proper switching angles. The output voltage levels are given by 2h+1, where h is the number of H-bridges used per phase. An 11-level cascade multilevel inverter based STATCOM is used in this work. Let the switching angles corresponding to H-bridges H_1, H_2, H_3, H_4 and H_5 are α_1, α_2, α_3, α_4, and α_5 respectively. The ac output phase voltage magnitude is given by $v_{an} = v_{a1}+v_{a2}+v_{a3}+v_{a4}+v_{a5}$ [10-13].

The switching angles α_1 … α_5, need to be selected properly as the harmonic distortion in the STATCOM output voltage depends very much on these angles. In the present work, these angles have been chosen in such a way that the harmonic distortion upto 49th order given by eqn. (1) is least [18].

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

In eqn. (1), *Vn*, is magnitude of nth harmonic voltage component where n = 1, 5, 7, 11, 13...49. Procedure for determination of switching angles is discussed thoroughly in [18]. Rotating switching scheme as discussed in [7] is also implemented here for maintenance of equal voltage across dc capacitors of individual H-bridges.

3. System Identification of CMLI STATCOM

System identification is a technique/process for determination of proper model of a dynamic system under study by using its input-output data set. Generally, the input-output data set are obtained either from time domain simulation or performing experiment on an actual physical system itself. The magnitude of input signal applied to the system should not disturb the normal operation in terms of its static and dynamic characteristics. A low magnitude pseudo random binary signal (PRBS) is generally used for this purpose [19-20].

The study system shown in [19] has been used for the determination of models of a CMLI based STATCOM using system identification technique. The relevant data of this system are given in the appendix. As discussed in [17,19], for a direct control, transfer functions between modulation index (*m*) (input) and load voltage (v_l) (output) as well as between dc capacitor voltage (v_{dc}) (output) and load angle (φ, input) are identified by following methods as described in [19-22] for proper design of parameters of PI controllers [19]. All simulations for determination of identified models have been carried out in the MATLAB/SIMULINK and SimPower Systems blocksets and system identification toolbox [22].

3.1 Identified Transfer Functions

3.1.1 Load voltage (Δv_l) versus modulation index (Δm)

The transfer function identified beween load voltage (Δv_l) and modulation index (Δm) is given in eqn. (2) [19].

$$G_{I1}(s) = \frac{\Delta v_l(s)}{\Delta m(s)} = \frac{20.28(s+434.13)}{(s+109.5 \pm j86.42)} \tag{2}$$

3.1.2 Total capacitor voltage versus load angle

By adopting a similar procedure, the identified transfer function between v_{dc} and φ is given by [19];

$$G_{I2}(s) = \frac{\Delta V_{dc}(s)}{\Delta \Phi(s)} = \frac{-56.11}{s+111.6} \tag{3}$$

4. Performance Validation

After identification of suitable system models, appropriate control systems can be designed for power system bus voltage regulation and dc capacitor voltage balance. In the present work, two PI controllers are designed for above purposes; one controller for load voltage regulation and the other for maintenance of constant dc capacitor voltage. The parameters of PI controllers have been designed by using Ziegler-Nichols method [16] and the design procedure has been carried out using MATLAB control system toolbox [23]. The obtained parameters of both the PI controllers are given in the appendix.

For validation of the identified models and performance evaluation of designed controllers, digital simulations of the system under study have been carried out using

MATLAB/SIMULINK under different load variations. The system simulated using MATLAB/SIMULINK is shown in Fig. 1. In Fig. 1, the loads connected through the circuit breakers CB2 and CB3 are extra load which have been used for testing the performance of the STATCOM under sudden load change conditions.

For testing the performance of the STATCOM under sudden load change conditions, following sequence of events has been followed in the simulation. The corresponding waveforms are shown in Figs. 2 (a) - (c) as obtained by the controllers designed using the identified models.

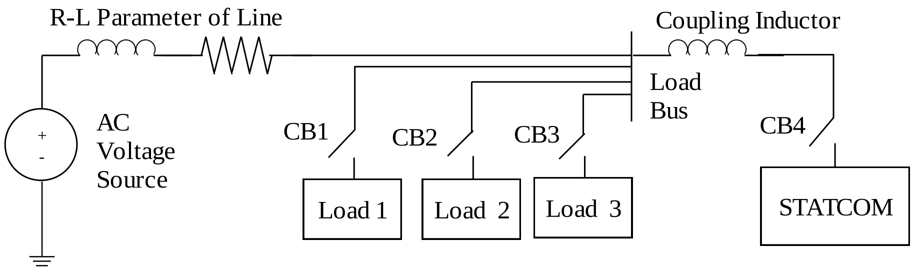

Fig. 1. MATLAB Simulation for performance evaluation of STATCOM.

a) Initially, all breakers except CB1 are kept open. An inductive load connected through CB1 draws reactive power from the power systems, thus maintaining load voltage below from 1 pu value (Fig. 2 (a)). At t = 0.2 sec., the STATCOM is connected at the load bus (with pre-charged CMLI dc capacitors) by closing the breaker CB4. From Fig. 2 it is observed that during the steady state operation, the load bus voltage is maintained at 1.0 pu by the STATCOM.

b) At t = 1 sec., an inductive load having active and reactive power of 0.4 and 0.6 pu respectively is connected to the load bus by closing the breaker CB2. As a result, the bus voltage falls immediately (Fig. 2(a)). To arrest this fall of bus voltage, the controller immediately increases v_c by increasing *m* (Fig. 2(b)). As a result, more reactive power is injected by the STATCOM and the bus voltage is again maintained at 1.0 pu at constant dc capacitor voltage.

c) At t = 2 sec., a capacitive load with active and reactive power of 0.2 pu and 0.6 pu respectively is connected to the load bus by closing the breaker CB3. As a result the bus voltage rises immediately (Fig. 2 (a)). To maintain the voltage at 1.0 pu, the controller decreases *m* (Fig. 2 (b)) thereby decreasing the STATCOM's output voltage. Consequently, reactive power is drawn by the STATCOM and the bus voltage again comes back to 1.0 pu very quickly at constant capacitors voltages.

d) At t = 3 sec., the inductive load is disconnected by opening the breaker CB2. As a result, the voltage again tends to increase (Fig. 2 (a)) and as evident from Figs. 2 (b) and 2 (c) the controller maintains the load bus voltage at 1.0 pu.

e) At t = 4 sec., the capacitive load is withdrawn by opening the breaker CB3. Consequently the load bus voltage tends to decrease (Fig. 2 (a)) and the controller again maintains the load voltage at 1.0 pu.

In Fig. 2 (c), the sum-total of all the dc capacitor voltages is shown. It may be noted that the capacitor voltages remain almost constant.

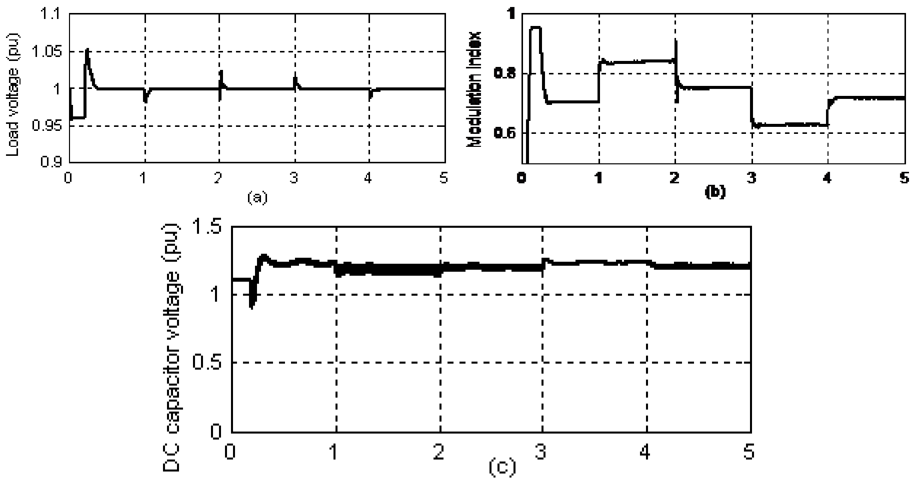

Fig. 2. (a) Load voltage regulation, (b) variation of modulation index and (c) total capacitor voltage variation.

5. Conclusion

In this paper, it is shown that the model of a CMLI STATCOM obtained by system identification technique represents its internal dynamics. Based on the identified transfer functions, parameters of two PI controllers one for load voltage regulation and other for dc capacitor voltage regulation purpose using Ziegler-Nichols approach have been designed. The performances of controllers designed using identified models have been compared through simulation results under conditions of system loading variations. For these cases, the load voltage control and dc capacitor voltage regulation performances of the CMLI STATCOM has been found to be quite satisfactory, thereby establishing the feasibility of the proposed system identification based voltage controller design methodology.

Appendix

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

Base voltage = 13.8kV, Base power = 5MVA, v_s = 1.0, ω = 314 rad./sec., X/R Ratio = 4, m_0 = 0.7000, R_S = 0.45Ω, L_S = 4.8 mH, R_C = 0.01 Ω, L_C = 28 mH, C = 4800 µF, v_{dcref} = 12500 V; R_L = 0.2 (pu), L_L = 0.4 (pu), R_P = 100π/4 (pu), load voltage controller's parameters(identified model): K_P = 5, K_I = 200; dc capacitor voltage controller's parameters (identified model): K_P = -3.15, K_I = -643.

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