## CHAPTER 3

### Chapter 3: VOLTAGE SOURCE INVERTER BASED STATCOM

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3.1 INTRODUCTION

Conventionally, two types of converters are in vogue: voltage-source (or voltage-fed) and current-source (or current-fed) converters (or inverters depending on power flow directions). Fig.3.1 shows the conventional three-phase voltage-source converter or Inverter (abbreviated as V-source converter or Inverter) structure. The DC voltage source can be a battery or fuel-cell stack or diode rectifier, and/or capacitor. The main circuit makes use of six switches. Each of these switches conventionally consists of a power transistor and a freewheeling or anti-parallel diode to furnish bidirectional flow of current and unidirectional blocking capability of voltage. The Voltage Source Converter (VSC) is extensively used[40], [47] for controlling induction motor and synchronous motor drives.

![Conventional three-phase V-source converter](image)

Fig.3.1 Conventional three-phase V-source converter
However, it has the following conceptual and theoretical barriers and limitations:

The AC output voltage is limited and cannot exceed the DC-rail voltage or the DC-rail voltage has to be greater than the AC input voltage. Therefore, the Voltage Source Inverter (VSI) is a buck (step-down) inverter for DC-to-AC power conversion and the Voltage Source Converter (VSC) is a boost (step-up) rectifier (or boost converter) for AC-to-DC power conversion. There may be a need for boost converter from DC-to-DC in order to provide a desirable additional output for such applications requiring high power. But this supplementary power converter-stage results in enhanced system’s cost besides lowering the efficiency levels.

The upper and lower devices of each phase leg cannot be gated-on simultaneously to avoid shoot-through condition. The shoot-through problem by electromagnetic interference (EMI) noise’s misgating-on is a major killer to the converter’s reliability. Dead time to block both upper and lower devices has to be provided in the V-source converter, which causes waveform distortion, etc. An output LC filter is needed for providing a sinusoidal voltage compared with the current-source inverter, which causes additional power loss and control complexity.
3.2 DEVELOPMENT OF SIMULINK MODEL OF THE VSI-BASED STATCOM

The Voltage Source Converter or Inverter (VSC or VSI) is the building block of a STATCOM and other FACTS devices. The Orcad diagram of Voltage Source Inverter (VSI) based STATCOM is shown in Fig.3.2. It consists of a power circuit and a control circuit. The power circuit comprises an VSI based inverter, a DC capacitor and output filter. Generation of the required pulses for the MOSFETs is achieved through pulse generator. This simple inverter produces a square voltage waveform as it switches the DC voltage source on and off. The basic objective of the VSI is to produce AC voltage with minimal harmonic distortion. For medium power applications MOSFETs are used for switching. The switches1,2 and 3, 4 are alternatively switched-on to produce square wave output. The large capacitor present at the input side acts as a voltage source. The drawback of the proposed VSI is that it has current spikes.
3.3 SIMULATION RESULTS

3.3.1 Two-bus Open loop system for sag compensation

Circuit model of two-bus system is shown in Fig.3.3. Additional load can be added in parallel by closing the breaker in series with the load2 as shown in Fig.3.3. Scopes are used to display the voltages across load1 and load2. The voltage across load1 decreases when load2 is switched at t=0.3sec. The voltage across load1 and load2 are shown in Fig.3.4.
Fig. 3.3 Circuit model of the two-bus system

Fig. 3.4 Voltage across load and load-2

Circuit model of the two-bus system with the VSI-based STATCOM for sag compensation is shown in Fig. 3.5. The voltage across load1, load2 and STATCOM of the two bus system with VSI-based STATCOM are shown in Fig. 3.6. The RMS voltage across load1 and the RMS current of the two bus system with VSI-based STATCOM are shown in Fig. 3.7 and Fig. 3.8 respectively. The real and reactive powers in load1 of the two bus system with VSI based STATCOM are shown in Fig. 3.9 and Fig. 3.10 respectively. The FFT analysis for the voltage of the two bus system for sag compensation is shown in Fig. 3.11. The THD is 2.08%.
Fig. 3.5 Circuit model of the two-bus system with the VSI-based STATCOM for sag compensation.

Fig. 3.6 Voltage across load1, load2 and STATCOM of the two bus system with VSI-based STATCOM.
Fig. 3.7 RMS voltage across load1 of the two bus system with VSI-based STATCOM

Fig. 3.8 RMS current through load1 of the two bus system with VSI-based STATCOM

Fig. 3.9 Real power in load1 of the two bus system with VSI-based STATCOM
Fig. 3.10 Reactive power in load 1 of the two bus system with VSI-based STATCOM

Fig. 3.11 FFT analysis for the voltage of the two bus system for sag compensation

3.3.1.1 Open loop two-bus system for swell compensation

Circuit model of two-bus system for swell compensation with the VSI-based STATCOM is shown in Fig. 3.12. Two loads are connected in parallel. The second load can be removed by opening the breaker shown in Fig. 3.12 to create swell condition. Scopes are used to display the voltages across load 1 and load 2. The second load is removed at the instant t=0.3 sec. The voltage across load 1 increases as
shown in Fig.3.13. The voltage across load1 and load2 of the two bus system for swell compensation is shown in Fig.3.13.

The RMS voltage across load1 of the two bus system for swell compensation is shown in Fig.3.14. The real and reactive powers in load1 of the two bus system for swell compensation are shown in Fig.3.15 and Fig.3.16 respectively. The FFT analysis of the two bus system for swell compensation is shown in Fig.3.17.

The real and reactive powers of load2 are not affected by the change in the load. The THD content for the output voltage of the inverter is 2.33%.

Fig.3.12 Circuit model with the VSI-based STATCOM for swell compensation
Fig. 3.13 Voltage across load 1 and load 2 of the two bus system for swell compensation

Fig. 3.14 RMS voltage across load 1 of the two bus system for swell compensation

Fig. 3.15 Real power in load 1 of the two bus system for swell compensation
Fig.3.16 Reactive power in load1 of the two bus system for swell compensation

Fig.3.17 FFT analysis for the voltage of the two bus system for swell compensation

**3.3.2 Eight-bus system**

The model of the eight-bus system without STATCOM is shown in Fig.3.18. The voltage across load1 of the eight bus system is shown in Fig.3.19. The real and reactive powers in load1 of the eight bus system are shown in Fig.3.20. The eight-bus system with the VSI-based STATCOM is shown in Fig.3.21. The voltage across load1 of the eight bus system with STATCOM is shown in Fig.3.22. The real and
reactive powers in load$1$ of the eight bus system with STATCOM are shown in Fig.3.23. The FFT analysis for the voltage across load$1$ of the eight bus system with STATCOM is shown in Fig.3.24. The THD is $0.45\%$. The THD is minimal due to the presence of LC filter in the output of inverter.

Fig.3.18 Model of the eight-bus system without STATCOM

Fig.3.19 Voltage across load$1$ of the eight bus system
Fig. 3.20 Real and reactive powers in load1 of the eight bus system

Fig. 3.21 Model of the eight-bus system with the VSI-based STATCOM
Fig. 3.22 Voltage across load1 of the eight bus system with STATCOM

Fig. 3.23 Real and reactive powers in load1 of the eight bus system with STATCOM

Fig. 3.24 FFT analysis for the voltage across load1 of the eight bus system with STATCOM
3.3.3 Fourteen-bus System

The fourteen-bus system without STATCOM is shown in Fig.3.25. Extra load can be added in parallel by closing the breaker shown in Fig.3.25. Scopes are used to display the voltages across load1 and load2. The second load is connected at the instant $t=0.3\text{sec}$. The voltages across load1 and load2 of the fourteen-bus system are shown in Fig.3.26. The voltage across load1 decreases when load2 is switched-on.

The real and reactive powers in load1 of the fourteen-bus system are shown in Fig.3.27. The fourteen-bus system with the VSI-based STATCOM is shown in Fig.3.28. The voltages across STATCOM, load1 and load2 of the fourteen bus system with the VSI based STATCOM are shown in Fig.3.29. The real and reactive powers in load1 of the fourteen bus system with the VSI based STATCOM are shown in Fig.3.30. The FFT analysis for the voltage of the fourteen bus system with VSI based STATCOM is shown in Fig.3.31.
Fig. 3.25 The fourteen-bus system without STATCOM

Fig. 3.26 Voltage across load1 and load2 of the fourteen-bus system

Fig. 3.27 Real and reactive powers in load1 of the fourteen-bus system
Fig. 3.28 The fourteen-bus system with the VSI-based STATCOM

Fig. 3.29 Voltage across STATCOM, load1 and load2 of the fourteen bus system with the VSI-based STATCOM
Fig. 3.30 Real and reactive powers in load1 of the fourteen bus system with the VSI-based STATCOM

Fig. 3.31 FFT analysis for the voltage of the fourteen bus system with VSI based STATCOM
3.3.3.1 Fourteen-bus closed loop system using PI-Controller

SIMULINK model of fourteen-bus closed loop system using the VSI-based STATCOM is shown in Fig.3.32. The STATCOM is connected at bus4. The closed loop system is designed to compensate the sag that occurs in the receiving end voltage. The load voltage is sensed and it is rectified using an uncontrolled rectifier. The error is obtained after making a comparison of this value with the reference value, which is processed by a PI controller. The required voltage can be obtained by adjusting the pulse width through the output of PI controller. The STATCOM output voltage is shown in Fig.3.33. The RMS voltage across load1 with STATCOM is shown in Fig.3.34 and its value is 4000V. The real and reactive powers in load1 are shown in Fig.3.35 and their values are $2\times10^5$ Watts and $6\times10^4$ VARs respectively.
Fig. 3.32 SIMULINK model of fourteen-bus closed loop system with VSI-based STATCOM employing PI-controller.

Fig. 3.33 STATCOM Output voltage
3.3.3.2 Fourteen-bus closed loop system using PID-Controller

SIMULINK model of fourteen-bus closed loop system with VSI-based STATCOM employing PID controller is shown in Fig.3.36. The STATCOM is connected at bus4. The closed loop system is designed to compensate the sag that occurs in the receiving end voltage. The load voltage is sensed and it is rectified using an uncontrolled rectifier. The error is obtained after making a comparison of this value with the reference value, which is processed by a PID controller. The required
voltage can be obtained by adjusting the pulse width through the output of PID controller. The output voltage of STATCOM is shown in Fig.3.37 and its value is 4000V. The RMS voltage across load1 with STATCOM is shown in Fig.3.38. The real and reactive powers in load1 are shown in Fig.3.39 and their values are $2\times10^5$ Watts and $6\times10^4$ VARs respectively. The comparison of the time domain parameters with PI and PID controllers are given in Table 3.1. It can be seen that with PID controller peak time, settling time and steady state error are reduced.

Fig.3.36 SIMULINK model of fourteen-bus closed loop system with VSI-based STATCOM employing PID-controller.
**Fig. 3.37** STATCOM Output voltage

**Fig. 3.38** RMS voltage across load1

**Fig. 3.39** Real and Reactive powers in load1
Table 3.1 Summary of time domain parameters with VSI based STATCOM using PI and PID controllers

<table>
<thead>
<tr>
<th>Controller</th>
<th>Peak time (s)</th>
<th>Settling time (s)</th>
<th>Steady state error (V)</th>
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<tr>
<td>PI</td>
<td>0.35</td>
<td>0.5</td>
<td>3.2</td>
</tr>
<tr>
<td>PID</td>
<td>0.31</td>
<td>0.39</td>
<td>2.4</td>
</tr>
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3.3.4 Two-bus closed loop system for sag compensation

SIMULINK model of closed loop system employing the VSI-based STATCOM is shown in Fig.3.40. The closed loop system is designed to compensate the sag that occurs in the receiving end voltage. The load voltage is sensed and rectified using an uncontrolled rectifier. The error is obtained after a comparison of this value with the reference value. A PI controller processes this error. The comparator compares the output of PI controller with the saw tooth voltage. When the output of the PI increases, the pulse width decreases and vice-versa. The voltage across load1 and current through load1 of the two bus closed loop system with STATCOM are shown in Fig.3.41. The RMS value of receiving end voltage of the two bus closed loop system with STATCOM is shown in Fig.3.42. The RMS value of the current through the load1 of the two bus closed loop system with STATCOM is shown in Fig.3.43. The real power output of the two bus closed loop system with STATCOM is shown in Fig.3.44. The reactive power output of the two bus closed loop system is shown in Fig.3.45. The power decreases during the sag period and comes back to the normal value due to the
action of the closed loop system. The FFT analysis for the output voltage of the two bus closed loop system with STATCOM is shown in Fig.3.46. The THD content is 1.37%.

Fig.3.40 SIMULINK model of the closed loop system with the VSI-based STATCOM
Fig. 3.41 Voltage across load1 and current through load1 of the two bus closed loop system with STATCOM

Fig. 3.42 RMS voltage of load1 of the two bus closed loop system

Fig. 3.43 RMS current in load1 of the two bus closed loop system with STATCOM
Fig. 3.44 Real power in load 1 of the two bus closed loop system with STATCOM

Fig. 3.45 Reactive power in load 1 of the two bus closed loop system with STATCOM

Fig. 3.46 FFT analysis for the voltage of the two bus closed loop system with STATCOM
### 3.3.4.1 Two-bus closed loop system for swell compensation

SIMULINK model of the two-bus closed loop system with the VSI-based STATCOM for swell compensation is shown in Fig.3.39. The closed loop system is designed to compensate the swell that occurs in the receiving end voltage. The actual voltage is sensed and its RMS value is obtained. This value is compared with the reference value and the error is obtained. A PI controller processes this error and the PI controller’s output readjusts the pulse width provided to the inverter’s switching device. When the swell occurs, the control system works in such a way, that the pulse width is reduced. Thus, the voltage at the receiving end is reduced to the normal value. The voltage across STATCOM, load1 and load2 of the two bus closed loop system with STATCOM for swell compensation is shown in Fig.3.40. The RMS value of receiving end voltage of the two bus closed loop system with STATCOM for swell compensation is shown in Fig.3.41. The real power output of the two bus closed loop system with STATCOM for swell compensation is shown in Fig.3.42. The reactive power output of the two bus closed loop system with STATCOM for swell compensation is shown in Fig.3.43. The power increases during the swell period and reduces to the normal value due to the action of the closed loop system. FFT analysis for the output voltage of the two bus closed loop system with STATCOM for swell compensation is shown in Fig.3.44. The THD content is 1.34%.
Fig. 3.47 SIMULINK model of the two-bus closed loop system with the VSI-based STATCOM for swell compensation

Fig. 3.48 Voltage across STATCOM, load1 and load2 of the two bus closed loop system with STATCOM for swell compensation
Fig. 3.49 RMS voltage across load 1 of the two bus closed loop system with STATCOM for swell compensation.

Fig. 3.50 Real power in load 1 of the two bus closed loop system with STATCOM for swell compensation.

Fig. 3.51 Reactive power in load 1 of the two bus closed loop system with STATCOM for swell compensation.
Fig.3.52 FFT analysis for the voltage of the two bus closed loop system with STATCOM for swell compensation

3.4 CONCLUSION

This chapter presents the modeling and simulation of two, eight and fourteen bus systems with the VSI-based STATCOM system. Sag compensation system and voltage injection system using VSI are simulated. It is found that the VSI-based STATCOM can be used to compensate the voltage drop. The voltage sag and swell are compensated by using closed loop systems.