CHAPTER - 5

MODELING AND SIMULATION OF INDUCTION FURNACE USING DISTRIBUTED STATIC COMPENSATOR

Over the past few decades, application of a large variety of non-linear loads for various operations in the industry has resulted in power quality issues, such as harmonic distortion and reactive power problems, in the supply network. Harmonics associated with the operation of an induction furnace under varying load conditions result in huge power losses and have a negative effect on nearby loads. The aim of this chapter is to present harmonic mitigation using a Distribution Static Compensator (DSTATCOM) to improve the power quality of a steel plant employing an induction furnace. A Simulink model of the induction furnace, whose performance matches the real-time data obtained from a steel plant induction furnace in operation, is designed. The performance with the application of three topologies, i.e. low level (7-level), intermediate level (11-level) and high level (15-level), of Cascaded Multilevel Inverter (CMLI), based DSTATCOM is evaluated and compared. The results show remarkable improvement in the voltage profile and Total Harmonic Distortion (THD) of the induction furnace.

An induction furnace is widely preferred in the steel industry. It injects a significant amount of harmonic currents leading to voltage imbalance and voltage fluctuations in the supply network [122, 123]. Harmonics in the supply are responsible for various adverse effects, like transformer losses, power factor reduction, measurement errors, increased heating losses, efficiency reduction. They also affect other consumers linked to the same supply network [1]. Initially, a number of control schemes were proposed by various researchers to overcome the power quality problems due to non-linear loads, such as active filters [124], passive filters [125] and hybrid filters [126]. Then, the advanced power electronics based custom power device technology came into action in which the devices can be connected in series and/or parallel with the system depending upon the device configuration.

A Cascaded Multilevel Inverter (CMLI) based Distribution Static Compensator (DSTATCOM) is one such type of custom power device which is connected in parallel to
the supply network feeding the induction furnace. It has the ability to produce high voltage output without the use of a transformer and can be applied very effectively to cancel the harmonics produced by the non-linear loads. Various configurations of DSTATCOM for power quality improvement, such as self-tuning filter based control algorithm [78], three phase Voltage Source Converter (VSC) having neutral at DC bus [127], voltage regulation improvement using shunt compensator [128], compensating non-linear loads using anti-Hebbian control algorithm [129], etc., have been investigated. DSTATCOM has been also found suitable in other applications like aircraft electrical systems [130], off-shore oil field applications [131] and wind generation applications [132].

The power quality problems can be mitigated using DSTATCOM by two ways. While operating in the current control mode, it balances the supply current by injecting the reactive power to the load current at the point of common coupling (PCC). It cancels the load waveform distortion and makes it sinusoidal by harmonic reduction [133]. In the voltage control mode, it regulates the voltage at PCC using a reference value thereby protecting the system from various voltage unbalances [134, 135].

Different control algorithms for DSTATCOM have been also proposed by the researchers from time to time. In the Adaptive control strategy, the system is based on an Artificial Immune System and the control parameters are measured using particle swarm optimization technique [136]. The control parameters can be modified online, thereby providing adaptive characteristics to the system. DC voltage at the bus is converted into AC using a VSC which is proportional to the output fundamental frequency voltage component and the voltage can be regulated accordingly. This control technique is preferable under unbalanced load conditions so as to improve the harmonic distortion and improve power quality. A battery storage system along with a DSTATCOM is preferable for the wind energy systems, which helps in the mitigation of various power quality disturbances owing to the fluctuating nature of the wind [137]. Some investigators have used DSTATCOM for power quality improvement in the electric arc furnaces for flicker removal [138, 139]. Using simulation-based techniques, DSTATCOM was also proposed for power quality improvement in the induction furnace [140, 141].
It is noted from the literature that, a DSTATCOM is not used for the exclusive study of an induction furnace. Only simulation-based techniques are employed for the analysis of an induction furnace. Moreover, these simulation results are not compared with the actual field measurements.

Use of a CMLI based DSTATCOM is presented in this chapter to improve the power quality degradation caused by an induction furnace. Three levels, i.e. seven-level, eleven-level, and fifteen-level, are chosen among the various topologies of CMLI and their performance is compared through simulations performed on a test system. The performance of the developed test system model matches the experimental data obtained by means of a power quality analyzer from an operating induction furnace in a steel plant. Simulation studies have been performed to study the problem of harmonics and voltage sag mitigation. Other power quality problems, such as flicker, are not considered because it is less prevalent in the induction furnace, unlike an electric arc furnace.

5.1 DIFFERENT CONTROL STRATEGIES OF DSTATCOM

Various power quality problems can be addressed by two approaches. The first approach is to be possible through consumer side and the second approach is through utility side. The consumer side approach involves load conditioning, which ensures that the connected equipment should not be sensitive enough to power quality disturbances, i.e. if any voltage dip or voltage swell occurs, then it may not affect the operation of the equipment. The other solution is to install line conditioning filters that can counteract such types of disturbances. They may involve PWM techniques and can be connected in series or parallel to the system. DSTATCOM is a custom power device which is used to balance current and remove harmonics from it. It is also used to regulate the load voltage thereby improving the power factor. The main element of DSTATCOM is VSC which provides quite good voltage regulation. The DC voltage of VSC is regulated by means of different control techniques using a PI controller. However, the performance of the system is affected due to the variation in its connected load. Hence under these conditions, the PI controller is not preferred. There are other control strategies also, but the type of control depends on the system loading conditions.
In order to compensate current harmonics on the load side, series active filters acting as a controllable voltage source should be connected in concurrence with shunt passive filters which are acting as a controllable current source. This is possible using PWM inverters, a DC bus, and any reactive element. This whole system configuration can play a major role in improving power quality problems. DSTATCOM is also referred as a current controlled shunt active power filter. It consists of a controller, VSC, an energy storage device and an optional filter as shown in Figure 5.1.

![Fig. 5.1: General layout of DSTATCOM](image)

The DC voltage in the storage device is converted into AC output voltage using VSC. The phase and magnitude of this AC voltage are adjusted to control active and reactive power between DSTATCOM and supply system. Thus, active and reactive powers can be generated or absorbed using such configuration. The following main purposes are served by DSTATCOM:

1. Power factor correction
2. Reactive power compensation
3. Harmonics mitigation
4. Voltage Regulation

The common control strategies of DSTATCOM are shown below. Each strategy is having its own merits and demerits as described below:
1. **PWM Control**: In this type of control, only RMS voltages measured at PCC are considered instead of reactive power. The VSC provides a PWM control technique which provides better voltage regulation in the system without any switching losses [142]. Also, the converter efficiency can be enhanced using high switching frequency.

2. **Adaptive Control Strategy**: This control strategy is based upon Artificial Immune System (AIS) in which the control parameters are measured using particle swarm optimization technique [136]. The control parameters can be modified online thereby providing adaptive protection to the system. The DC voltage at the bus is converted into AC using VSC which is proportional to the output fundamental frequency voltage component. Thus, the voltage can be regulated accordingly. In order to keep output voltage in phase with bus voltage, the phase angle should be maintained. The adaptive control strategy process is shown in Figure 5.2.

![Figure 5.2: Adaptive control strategy of DSTATCOM](image)

3. **Flexible Operation**: DSTATCOM can balance the voltage of a supply bus and try to make it sinusoidal while operating in voltage control mode [143]. However, in the current control mode, it cancels the load waveform distortion and makes it sinusoidal by harmonic reduction. This control technique is preferable in unbalanced load conditions so as to improve the harmonic distortions and improve the power quality.
4. **The lookup table and super capacitor energy storage system:** In this control technique, DSTATCOM and super capacitor energy storage systems are integrated and PI controller is used to providing feedback regarding appropriate gain under fault conditions [144]. The super-capacitor energy storage system along with the feedback process helps in mitigation of transient conditions, voltage sag removal and improves the dynamic response of the system.

5. **Battery Storage System:** This system is generally preferable in wind energy systems. The battery energy storage along with DSTATCOM helps in mitigation of various power quality disturbances owing to fluctuating nature of wind. This system is somehow costly as compared to the others because of the additional cost of batteries involved in the system.

### 5.2 CMLI BASED TOPOLOGIES OF DSTATCOM

Out of the various configurations of multilevel inverters, Cascaded Multilevel Inverter (CMLI) is one of the preferred topologies among the various types of multi-level converter family. As compared to the multi-pulse converter, it requires fewer components and also there is no need of a special transformer. In the proposed topologies of CMLI, the fundamental frequency switching scheme has been implemented resulting in reduced switching losses as compared to the Pulse Width Modulation (PWM) technique. In the basic configuration of CMLI, different H-bridge inverter units are connected in series and each of these units has separate DC source as shown in Figure 5.3 [146, 147].

Every unit is able to produce three different levels of voltages, i.e. $+V_{dc}$, $-V_{dc}$ and zero, and the DC source is connected to the AC output side by means of switches. The sum of the output of all the H-bridge units connected in series gives the combined output voltage. Configurations of 7-level, 11-level, and 15-level CMLIs have been designed in Simulink as shown in Figures 5.4, 5.5 and 5.6 respectively. Each topology is characterized by the number of H-bridges and DC sources are replaced by capacitors to reduce cost.
Fig. 5.3: Basic CMLI configuration

Fig. 5.4: 7-level CMLI topology
The function of rotating switch is to compensate the conduction losses of H-bridges due to different values of the switching angles of H-bridges. The number of output voltage levels is expressed as \((2h+1)\), where \(h\) is the number of H-bridges used per phase [145]. Thus, if three H-bridges are used, then the CMLI configuration is of seven levels and so on.

The magnitude of the AC side output voltage per phase for five H-bridges is given by the expression:

\[
V_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5} \tag{5.1}
\]

where, \(v_{a1}, v_{a2}, v_{a3}, v_{a4}\) and \(v_{a5}\) are the output voltages of bridges \(H_1, H_2, H_3, H_4\) and \(H_5\), respectively. The Fourier series expression of this staircase AC voltage of the CMLI at the fundamental frequency is given by:

\[
v_{an}(\omega t) = \sum_{k=1,3,5,...}^{\infty} \frac{4V_{dc}}{k\pi} \left[ \cos(k\alpha_1) + \cos(k\alpha_2) + \cdots \cos(k\alpha_h) \right] \sin(k\omega t) \tag{5.2}
\]

**Fig. 5.5:** 11-level CMLI topology
Fig. 5.6: 15-level CMLI topology

It is necessary to calculate the switching angles to attain a preferred maximum voltage of $V_i$ i.e. $0 \leq \alpha_1 < \alpha_2 < \cdots < \alpha_h \leq 90^\circ$. The phase voltage harmonics of lower order are zero in this process. The fundamental voltage can be expressed in terms of the switching angles using equation (5.2) as:

$$V_1 = \frac{4V_{dc}}{\pi} (\cos(\alpha_1) + \cos(\alpha_2) + \cdots + \cos(\alpha_h))$$  \hspace{1cm} (5.3)

The ratio of the fundamental output voltage $V_1$ to the maximum obtainable fundamental voltage $V_{1max}$ is known as Modulation index. When all the switching angles are zero, the maximum fundamental voltage obtained is given by:

$$V_{1max} = \frac{4hV_{dc}}{\pi}$$  \hspace{1cm} (5.4)

The modulation index is given by the expression:

$$M = \frac{\pi V_1}{4hV_{dc}}$$  \hspace{1cm} (5.5)
As five H-bridges are used for an 11-level CMLI, five degrees of freedom (DOF) are existing in this case. One DOF is used in controlling the fundamental voltage magnitude and the other four are used for the elimination of fifth, seventh, eleventh and thirteenth level harmonics.

### 5.3 EXPERIMENTAL SETUP AND MEASUREMENTS

Power quality analyzer is an instrument which is exclusively used for the measurements of different types of power quality problems like voltage sag, swell, interruption, harmonics etc. In this case, the measurements using this equipment are recorded for a complete interval of two hours, in which the instances of the furnace loading and unloading are covered. The period of two hours is selected because a furnace usually takes around two hours for loading, melting, processing, and unloading the scrap material. The voltage and current THD towards the load side are measured and is shown in Figures 5.7 and 5.8 respectively. Based on these measurements, a Simulink circuit is designed and voltage and current FFT is again measured using FFT analysis. Both the measurements are almost same which proves the validity of the circuit. Further, a CMLI based DSTATCOM as discussed in above sections is connected to the circuit and the improvement in voltage and current FFT towards the load side is noticed. It shows significant improvement in the voltage and current THD which proves the effectiveness of this circuit.

![Fig. 5.7: Voltage harmonics measurement before DSTATCOM](image-url)
5.4 SIMULATION OF INDUCTION FURNACE USING DSTATCOM

Block diagram of an industrial steel plant employing an induction furnace is shown in Figure 5.9. Study of the induction furnace has been carried out on a medium frequency range of 500 Hz for ease of melting process because scrap melting is tranquil at a higher frequency. This is possible by using a power and frequency unit in the induction furnace which chooses the desired frequency and power as per requirements. The frequency variation is possible by using the inverter circuit which raises the supply frequency of 50 Hz to 500 Hz.

There is a metal loading unit in the induction furnace circuit which describes the different types of metal scrap for the manufacturing process. Ratings of all the components involved in the furnace operation and used for designing the model of an induction furnace unit in MATLAB/Simulink software are shown in Table 5.1. Input supply of 11 kV, 50 Hz is stepped down to 415 V using a step down three-phase transformer and is then converted
to 700 V DC using two rectifiers having twelve pulse configuration. The test system specifications are shown in Table 5.1.

Table 5.1: Test system specifications of DSTATCOM

<table>
<thead>
<tr>
<th>S. No.</th>
<th>System Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Supply transformer</td>
<td>3-Φ, Y-Y-Δ, 4 MVA, 11/0.415 kV, 50 Hz</td>
</tr>
<tr>
<td>2.</td>
<td>Inverter</td>
<td>Single phase, IGBT Based, 500 Hz</td>
</tr>
<tr>
<td>3.</td>
<td>Induction furnace</td>
<td>7.5 Ton, 12 pulses, Megatherm make</td>
</tr>
<tr>
<td>4.</td>
<td>Electrical equivalent parameters of furnace</td>
<td>LC Branch= 400 mH, 50 µF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RL Branch= 100 mH, 10 Ω</td>
</tr>
<tr>
<td>5.</td>
<td>Injection transformer</td>
<td>1:10, R = 0.001 pu, X = 0.04 pu</td>
</tr>
<tr>
<td>6.</td>
<td>DC link capacitor</td>
<td>8000 µF</td>
</tr>
<tr>
<td>7.</td>
<td>Modulation index of 7-level CMLI for three H-bridges</td>
<td>0.2087, 0.4251, 0.9371</td>
</tr>
<tr>
<td>8.</td>
<td>Modulation index of 11-level CMLI for five H-bridges</td>
<td>0.1532, 0.2234, 0.4357, 0.8250, 1.053</td>
</tr>
<tr>
<td>9.</td>
<td>Modulation index of 15-level CMLI for seven H-bridges</td>
<td>0.1039, 0.2054, 0.4905, 0.6679, 0.7423, 1.0288, 1.3884</td>
</tr>
<tr>
<td>10.</td>
<td>PI Controller parameters</td>
<td>Kp= 10, Ki= 200</td>
</tr>
<tr>
<td>11.</td>
<td>Coupling inductor</td>
<td>30 mH</td>
</tr>
<tr>
<td>12.</td>
<td>Nominal System Voltage</td>
<td>700 V</td>
</tr>
<tr>
<td>13.</td>
<td>Power quality analyzer</td>
<td>Fluke make 435 Series-II</td>
</tr>
</tbody>
</table>

The induction furnace is connected in the circuit through circuit breaker 1 and CMLI based DSTATCOM is connected in parallel to the induction furnace load through circuit breaker 2. The modulation index for different H-bridges is calculated using Newton-Raphson method. The circuit breakers have their pre-defined time settings. The devices are switched at the fundamental frequency (500 Hz) to reduce the switching losses. The indirect control scheme [145] by varying DC capacitor voltage at a fixed switching angle/modulation index has been implemented to vary the output voltage magnitude produced by the DSTATCOM.
A circuit diagram of the industrial steel plant involving both DSTATCOM and induction furnace is also shown in Figure 5.10.

![Circuit diagram of Induction furnace using DSTATCOM](image1)

**Fig. 5.10:** Circuit diagram of Induction furnace using DSTATCOM

The firing angle of the rectifiers is controlled through a synchronized pulse converter, the detailed configuration of which is shown in Figure 5.11.

![Rectifier firing circuit](image2)

**Fig. 5.11:** Rectifier firing circuit

The capacitor bank after the DC choke coil increases the magnitude of voltage up to the desired level. The two-level single phase full bridge inverter circuit then converts this DC voltage into a single phase AC voltage and enhances the supply frequency of the main supply from 50 Hz to 500 Hz. The voltage at the coil that melts the scrap material is 700 V at 500 Hz and the energy consumption of the coil is around 2500 kW.
The induction furnace load parameters were obtained from the steel industry and thus modeled in terms of its electrical equivalent parameters in the Simulink as shown in Figure 5.12.

![Fig. 5.12: Electrical equivalent Induction furnace model](image)

The series inductance represents the main induction furnace coil. Since it is a coreless induction furnace, hence the capacitor represents the scrap material acting as a dielectric medium inside the induction furnace. It is also used to attain a controllable resonance of the frequency circuit. The resistance is the inherent part of the inductance coil and the parallel inductor is acting as a snubber circuit which is used to prevent any voltage spikes inside the induction furnace. All these parameters are connected in such a way that they represent a real induction furnace. The self-inductance of the furnace coil varies with the quality of scrap material thereby changing its resonant frequency. Thus, the furnace coil and the capacitor are in resonance whose frequency is controlled by the inverter circuit.

As circuit breakers 1 and 2 have their pre-defined time settings, the induction furnace load is connected to the circuit at time 0.1 s using circuit breaker 1 due to which the voltage magnitude decreases and voltage sag is introduced in the system. At the instant 0.2 s, DSTATCOM is connected in the circuit through circuit breaker 2, which removes the voltage sag completely and the system voltage towards the load side is restored to its normal limits. The complete voltage sag phenomenon is shown in Figure 5.13.
THD of both the voltage and current towards the load side is calculated before connecting the DSTATCOM in the circuit using FFT analysis in the Simulink platform and is shown in Figures 5.14 and 5.15, respectively. In the FFT window, THD is shown up to 20th order only i.e. 10 kHz for clarity, while the value of THD is due to harmonics content up to the 49th order because the fundamental frequency is 500 Hz.

Comparing Figures 5.7 with 5.14 and 5.8 with 5.15, it is seen that both the power quality analyzer results for the actual induction furnace and the results of the simulation model give almost the same voltage THD of around 74% and current THD of around 55% which verifies the validity of the Simulink model. The DSTATCOM circuit with three different topologies, as discussed above, is connected in the circuit one by one and the improvement in THD of both load voltage and the load current by 7-level, 11-level, and 15-level CMLIs is shown in Figure 5.16-5.21 respectively.

The FFT analysis of the load current waveform shows the improvement in load current THD content strictly according to IEEE-519 standards. The simulation results illustrate that by using multilevel inverter based DSTATCOM, voltage sag problem has been alleviated along with the significant improvement in its THD content.

**Fig. 5.13:** Voltage sag phenomenon of an Induction furnace using DSTATCOM
Fig. 5.14: Voltage FFT analysis for DSTATCOM

Fig. 5.15: Current FFT analysis for DSTATCOM
Fig. 5.16: Voltage FFT of 7-level CMLI

Fig. 5.17: Current FFT of 7-level CMLI
Fig. 5.18: Voltage FFT of 11-level CMLI

Fig. 5.19: Current FFT of 11-level CMLI
Fig. 5.20: Voltage FFT of 15-level CMLI

Fig. 5.21: Current FFT of 15-level CMLI
A summary of the results obtained using three levels towards the load side is shown in Table 5.2.

**Table 5.2**: Comparison of voltage and current THD for different level inverters

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Methodology</th>
<th>Before (%)</th>
<th>After (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7-level</td>
<td>11-level</td>
</tr>
<tr>
<td>1.</td>
<td>Voltage THD</td>
<td>74.81</td>
<td>14.62</td>
</tr>
<tr>
<td>2.</td>
<td>Current THD</td>
<td>54.20</td>
<td>6.09</td>
</tr>
</tbody>
</table>

### 5.5 RESULTS AND DISCUSSIONS

A Cascaded Multilevel Inverter (CMLI) based DSTATCOM has been chosen to improve the power quality in a steel manufacturing plant employing an induction furnace. A Simulink model of the furnace, that closely follows the performance of an operating induction furnace in a steel plant, under the same operating conditions, is developed. With the proposed DSTATCOM, the current THD of the induction furnace has improved from 54.20% to 6.09%, 1.31% and 1.05% using 7-level, 11-level, and 15-level DSTATCOM, respectively. Similarly, voltage THD has also been improved from 74.81% to 14.62, 8.44% and 8.05% by using 7-level, 11-level, and 15-level DSTATCOM, respectively.

Performance studies with three topologies of CMLI based DSTATCOM, low, intermediate and high level, show that improvement in THD by the 7-level CMLI is not as significant compared to the 11-level and 15-level CMLIs. Although the THD improvement by 15-level CMLI is the best, the cost of a 15-level CMLI is relatively much higher than that of the 11-level CMLI due to the much larger number of components. A comparison of results of the suggested approach shows significant improvement in the THD content of the system. Based on these studies, 11-level CMLI seems to be the best choice for effective THD improvement and voltage profile improvement in the case of an induction furnace.

The results also show that THD improvement by 7-level CMLI is not as much compared to the other two topologies. Although the current and voltage THDs of both 11-level and 15-level CMLIs do not differ very much and are according to IEEE-519
standards, the cost of a 15-level CMLI is much higher than that of an 11-level CMLI owing to the increase in a number of components and capacitors. It can be seen that the proposed approach is quite effective for power quality improvement in the induction furnace.