Design of STATCOM for reactive power control using multilevel inverter

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Abstract. STATCOM a power electronic based device is widely used for reactive power compensation. In the present work, a STATCOM is realized by employing a 3-level neutral point clamped inverter which is controlled by space vector pulse width modulation technique. Switching sequence for STATCOM is designed by minimizing the deviation in neutral voltage. Subsequently, the STATCOM is connected to the load side of a power network and by varying source voltage, reactive power control is accomplished resulting in voltage control of load side and improving the power quality of the network. The present work will be useful to the utilities dealing with reactive power and voltage control of AC transmission networks.

Keywords. Static Synchronous Compensator (STATCOM), Neutral Point Clamped (NPC), Multilevel Inverters, Pulse Width Modulation (PWM)

1. INTRODUCTION
Voltage control and reactive power compensation of a power system network are essential for maintaining the power quality. A good voltage profile, power factor and stability can be achieved by reactive power compensation. STATCOM is one of the shunt connected FACTS devices which is used for reactive power absorption or injection and network voltage control. Compared to series connected SSSC (Static Synchronous Series Compensator), STATCOM has following advantages like fast response and small size. Basically STATCOM comprises of voltage source converter where IGBT (Insulated-Gate Bipolar Transistor) or GCT (Gate-Commutated Thyristor) are used for switching. Whenever, a STATCOM is connected to a bus, it either absorbs or injects reactive power according to the need and thus voltage of the bus is regulated. When voltage generated (E) by STATCOM and bus voltage (V) are equal, it will not inject or absorb reactive power. If E>V, STATCOM act as capacitor and for E<V, STATCOM act as an inductor. As a result STATCOM draws capacitive or inductive reactive current and thus generates or absorbs reactive power respectively [1].

STATCOM can be realised in different ways. As multi pulse converters have several disadvantages namely lack of control in generated voltage, need of additional transformer and complicated control due to magnetics. So as its alternative, a multilevel converter can be used to overcome
the disadvantages of multi pulse inverters[2]. Multilevel inverters are combination of semiconductor switches, capacitors and diodes which result in stepped voltage as output. As number of levels increase, number of steps in output also increase which result in low harmonic distortion. However, this leads to complex control of the inverter [3].

Three basic configurations in multilevel converters widely used are, Diode clamped, Capacitor clamped and Cascaded converters. Amongst these three configurations, diode clamped configuration is widely used for high power applications [3]. Neutral Point Clamped(NPC) is a special case of diode clamped converter. NPC consists of clamping diodes and capacitors to produce AC voltage having multiple levels. Figure 1 shows the basic configuration of the three-level NPC.

DC voltage applied to the input side of the inverter is divided into three levels by using series connected capacitors. The DC bus capacitor is divided into two which forms neutral point. DC voltage applied in the dc side is equally shared between these capacitors. Midpoint of capacitors Z, shown in Figure 1 is the neutral point. The 3 levels of output of inverter are $V_{DC}/2$, $-V_{DC}/2$ and 0. [4]. As the output has three levels, it is known to be three level inverter. It is realised as STATCOM as both have same outputs.

Comparing with the conventional two level converter, realisation of STATCOM as multilevel voltage source converter has various advantages such as reduction of THD values and switching frequency [4,5]. Basic operational states of single leg of three-level NPC are shown in Table 1. The switching pulses can be provided by using carrier based, space vector or selective harmonics PWM. Carrier based technique has problem in controlling neutral point voltage. So space vector technique will be perfect for the control multilevel inverters [5-10]

| Switching State | S1 | S2 | S3 | S4 | Output Voltage |
|-----------------|----|----|----|----|----------------|
| P               | On | On | Off| Off| $V$            |
| O               | Off| On | On | Off| 0              |
| N               | Off| Off| On | On | -$V$           |

In [5] without any control circuit, balance of capacitor voltage is discussed. In [6] design and hardware implementation of 3-level NPC is presented. In [7] space vector PWM technique is applied to three-level NPC for balancing DC capacitor voltage. In [7] a simplified algorithm is proposed for reducing computational efforts in space vector PWM. However in [5]-[8], subdivision of regions in each sectors is not done which result in reduction of neutral voltage deviation. The present work focuses on the design of inverter and its realisation as STATCOM using space PWM technique and reduction of
neutral voltage deviation of the inverter. The work is applicable for proper control of reactive power and voltage of grid.

The present paper is summarized as follows. In to section 2, brief details about space vector PWM is discussed. In section 3, working of device and the problem is formulated. Complete inverter design is given in section 3. In section 4 simulation results with inverter incorporated power system network are provided. Finally conclusions are shown in section 5.

2. SPACE VECTOR PWM

Space vector PWM technique is one of the PWM techniques used in multilevel inverters for obtaining switching pulses. For a m-level, n-phase inverter, number of states available will be \( m^n \). So a 3-level, 3-phase inverter has 27 states. All these states have corresponding space voltage vectors. These vectors can be divided to zero, small, medium and large vectors. As zero vectors are redundant, total number of vectors reduces to 19, since there are 9 zero vectors. Among these vectors zero and large vectors don’t play any role in neutral point voltage deviation. This deviation is totally dependent on small and medium vectors.

Space vector PWM technique is based on volt-second balance principle discussed in [8]. Basically \( V_{ref} \) vector need to be determined correctly. This reference vector is the resultant of three nearest vectors depending on which region, reference vector belongs to and it is shown in (1). Suppose reference vector belongs to region 2 of first sector where, \( T_a, T_b, T_c \) are corresponding dwell times of vectors \( V_1, V_7, V_2 \), and \( T_s \) the sampling period. Then we get,

\[
V_1T_a + V_7T_b + V_2T_c = V_{ref}T_s
\]

\[
T_a + T_b + T_c = T_s
\]

(1)

By substituting voltage magnitude and corresponding angles of each vector in (1), dwell times related to vectors of the region are determined. Similarly dwell times for possible combinations in each region of each sector are found out.

3. PROBLEM FORMULATION

STATCOM connected in a power system is shown in Figure 2. Since the power system networks are interconnected and heavily loaded, fluctuations in voltage occurs due to the variations in load. This voltage variations result in poor power quality as well. Using the variable voltage source, here voltage can be varied as a part of problem formulation. This will result in large variation of load side voltage. STATCOM is connected to network through transformer. Whenever voltage variations occur, STATCOM starts compensating either by injecting or absorbing reactive power. The system parameters used in the present work related to the concerned network and inverter are as provided in Table 2.

![Figure 2. STATCOM connected in a Power System.](image-url)
3.1. Inverter Design

In the present work, inverter is fully controlled by space vector PWM. The three phase supply voltage has been given to space vector algorithm for generating gate pulses for inverter. Figure 3 shows the space vector diagram of three-level inverter [9]. This vector diagram is divided into 6 sectors and each sectors are subdivided to four regions. Division of regions are illustrated by dotted lines. To minimize neutral voltage deviation, two regions of each sector are again divided into two as-1a, 1b and 2a, 2b. After this division, one of the small vector can be considered as dominant vector.

Table 2. System and Inverter Parameters

| Parameters                   | Values                  |
|------------------------------|-------------------------|
| Network Voltage              | 440V(ph-ph)             |
| Frequency                    | 50Hz                    |
| Sampling Frequency           | 5kHz                    |
| Line Inductance              | 1.5mH                   |
| Filter Inductance            | 1mH                     |
| Inverter DC Input            | 400V                    |
| Number of switches in inverter | 12                     |
| Number of diodes in inverter | 14                     |
| Number of capacitors in inverter | 2                     |

![Figure 3. Space vector diagram of 3-level NPC](image)

from the selected three vectors for the calculation of \( V_{ref} \). For example, considering region 1a of sector 1, the three vectors used for calculation of \( V_{ref} \) are \( V_0, V_1 \) and \( V_2 \). As region 1a comes near to \( V_1 \), \( V_1 \) is then considered as dominant vector.

Using Clarke’s transformation, three phase supply components are converted to \( \alpha-\beta \) domain. By taking resultant of new components, \( V_{ref} \) is found using (2). The corresponding angle is also calculated to determine in which sector \( V_{ref} \) belongs to [11,12]. For simplicity all calculations have been done in first sector after finding out the exact location of \( V_{ref} \). Modulation index, which is involved as a major
parameter for the calculation of dwell times is determined using (3). As the input varies, corresponding modulation index also varies. So, once the input is given, after Clarke’s transformation $V_{ref}$ and angle corresponding to it are found out. Using this angle, sector and region of $V_{ref}$ are calculated and subsequently, dwell time is determined. Finally, on-time is calculated and with the help of this, PWM signal is obtained.

$$V_{ref} = V_\alpha + jV_\beta$$  \hspace{1cm} (2)

$$m = \frac{\sqrt{3}V_{ref}}{V_{dc}}$$  \hspace{1cm} (3)

The switching sequence is designed according to the conditions which result in minimization of neutral point voltage deviation. One of the major condition to be satisfied is the involvement of maximum two switches during the transition of state from one to another. On the basis of conditions to be satisfied for minimization, following sequences are designed as 7-segment switching so that symmetry is obtained as shown in Table 3. Sequence can also be written for even order harmonic elimination. Considering $V_{ref}$ in region 1a of first sector, sequence for even order harmonic elimination is given as

P00 – 000 – 00N – 0NN – 00N – 000 – P00

where P, O, and N are as defined in Table 1. Similarly the sequence can be written for remaining sectors by satisfying the conditions.

### 3.2. Symmetrical PWM Generation

The switching sequence can be plotted graphically for calculating on-time. For example, sequence for region 1a of first sector is drawn graphically and on-time is found out as shown in Figure 4. $T_a$, $T_b$ and $T_c$ are corresponding time of vectors $V_0$, $V_1$ and $V_2$ respectively. As two of the selected vectors belong to small vectors and $V_1$ dominates, the time is to be divided equally between $V_{1N}$ and $V_{1P}$. On-time of lower level switches will be compliment of that of upper level switches.

Once on-time calculation is done, it is then compared with a ramp of $T_s$ time period and the resulting pulse is given to switches to obtain the desired output. On-time calculation of first sector is shown in Table 4.

| Table 3. Switching Sequence for Sector I |
|---|---|---|---|---|---|
| 1a | 1b | 2a | 2b | 3 | 4 |
| 0NN | 00N | 0NN | 00N | 0NN | 00N |
| 00N | 000 | 00N | P0N | PNN | P0N |
| 000 | P00 | P0N | P0P | P0N | PPN |
| P00 | PP0 | P00 | PP0 | P00 | PP0 |
| 000 | P00 | P0N | P0P | P0N | PPN |
| 00N | 000 | 00N | P0N | PNN | P0N |
| 0NN | 00N | 0NN | 00N | 0NN | 00N |

By using the calculated time shown in Table 4, pulses can be generated for every sectors. Designed inverter is then connected to power system network through filter. Reactive power exchange
is done by device according to the need. Modulation index can be kept either fixed or variable. As input to space vector PWM varies, switching sequences will be generated according to those variations and so the proper pulses will be generated subsequently [12-15].

![Diagram](image)

**Figure 4.** On-time calculation of 1a region of sector

| Region | 1       | 1b      | 2       | 2b      | 3               | 4               |
|--------|---------|---------|---------|---------|-----------------|-----------------|
| Time   | 1a      | 1b      | 2a      | 2b      | 3               | 4               |
| S1a    | $T_a/4$ | $T_a/2+T_a/4$ | $T_a/2+T_a/4$ | $T_a/2-T_a/4$ | $T_a/2-T_a/4$ | $T_a/2-T_a/4$ |
| S2a    | $T_a/2$ | $T_a/2$  | $T_a/2$  | $T_a/2$  | $T_a/2$  | $T_a/2$  |
| S1b    | 0       | $T_a/4$  | 0       | $T_a/4$  | 0               | $T_a/2+T_a/4$ |
| S2b    | $T_a/2-T_a/4$ | $T_a/2$  | $T_a/2-T_a/4$ | $T_a/2$  | $T_a/2+T_a/4$ | $T_a/2$  |
| S1c    | 0       | 0       | 0       | 0       | 0               | 0               |
| S2c    | $T_a/4+T_b/2$ | $T_a/2-T_a/4$ | $T_a/4$  | $T_a/2+T_a/4$ | $T_a/4$  | $T_a/4$  |

**Table 4.** On-Time Calculated for Sector I

4. SIMULATIONS AND RESULTS

To illustrate the effectiveness of the designed multilevel inverter based STATCOM, it is installed in a power system which is simulated in MATLAB/Simulink. The simulink model of the inverter is as shown in Figure 5

Figure 9 shows the voltage on load side once device is connected indicating an improvement in the voltage profile.
Figure 5. Inverter model designed in SIMULINK

The line-line output voltage waveforms of 3-level NPC are as shown in Figure 6. Frequency of the system can be verified through waveform and it is coming to be 50Hz in this test system.

The designed inverter is then installed in a small power system network whose Simulink model is as Figure 7. Loading conditions are then varied to check the effectiveness of the inverter in maintaining a constant voltage profile. Using the three-phase variable source, voltage is varied. For a certain time period, voltage is decreased from 1p.u to 0.8p.u. And for other time period voltage is increased from 1.0p.u to 1.2p.u. which results in distortion. Three-phase supply is then connected to space vector control block. Whenever supply varies, output of STATCOM also changes.

Figure 8 shows the variation in voltage with power system which has a programmable source. This time inverter is not connected to network. Once device is connected, it starts compensation and results in voltage control.

Figure 6. Line-line output voltage waveform of 3-level NPC
Figure 7. Simulink model of network connected to inverter.

Figure 10 shows the active power-reactive power plot of load side without connecting the inverter to power system network. Figure 11 shows the compensation done by STATCOM when it is connected to load side. From these observations, it can be noted that device is been injecting and absorbing reactive power which results in better voltage profile and improves power quality of network.

Figure 8. Variation of voltage in load side without connecting STATCOM.

Figure 9. Load voltage after connecting STATCOM.
Figure 10. Active and reactive power variation in load side without connecting STATCOM.

Figure 11. Reactive power compensation by STATCOM.

5. Conclusion

The design of three-level NPC inverter and subsidiary control circuit of the network has been simulated. Detailed designing of the inverter has been accomplished so as to do the reactive power control. Space vector control of inverter has been obtained. Minimization of neutral point voltage deviation has been done by subdivision of space vector diagram. Subsequently, the device is connected to a small network and proper reactive power compensation has been achieved. As a result of this, enhancement of voltage profile and power quality has been obtained. Thus, realisation of STATCOM as 3-level NPC inverter which is controlled by space vector PWM is achieved and operation of STATCOM is verified in MATLAB/Simulink.

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