CONTROL DESIGN OF STATCOM USING FIVE LEVEL NEUTRAL POINT CLAMPED CONVERTER AND ITS APPLICATION TO REACTIVE POWER

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This paper deals with multilevel neutral point clamped (NPC) converter voltage source inverter applied as STATCOM. The proposed control with space vector modulation (SVM) switching and decoupled current control with IP controllers have been tested to prove the advantages of the proposed control. The effectiveness and validity of the controller system is supported by computer simulation. Simulation results obtained confirm that the controller has a very good performance, allowing compensation of capacitive or inductive. The simulation of the proposed system is developed using MATLAB, Simulink.

1. INTRODUCTION

Benefits of reactive power compensation are well known: increased stability, increased transmission capacity over existing lines, better voltage profile and decreased losses. The management of reactive power by traditional means has its drawbacks, depending on compensation technique used. These include a possibility of resonance, slow response, introduction of harmonics, rotational instability or management of reactive power which can be done only in discrete steps. Moreover, if capacitor banks are used (with or without thyristors), they occupy a considerable amount of real estate. The new generation of static compensator based on multilevel inverters have become an effective and practical solution for increasing power and reducing harmonics of ac waveforms. They are used for driving high-power medium-voltage induction motors and var compensation in flexible ac transmission systems (FACTS). The main advantages of multilevel PWM inverters are the following:

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The series connection allows higher voltage without increasing voltage stress on switches. This is necessary for high-power applications, such as traction systems, where the voltage applied to the induction motor is higher than one kV.

At the same switching frequency, a multilevel inverter can achieve lower harmonic distortion due to more levels of the output waveform in comparison to a single cell inverter. [1]

In this multilevel VSI based STATCOM category, there are mainly three different system configurations: 1) diode-clamped converter configuration [2, 3]; 2) flying-capacitor converter configuration [4, 5]; and cascading converter configuration [3, 5]. In this paper, five levels neutral point clamped and its application in reactive power compensation is proposed. The compensator power structure is presented in section 2, and the gating and control strategies are described in section 3, the modeling and control structure for reactive power is explained in section 4. Waveforms for injected reactive power and resulting line currents are obtained from the simulation Simulink/ Matlab.

2. **OPERATION OF STATCOM**

The STATCOM employs is a solid state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals (ac), when it is fed from an energy source or an energy storage device of appropriate capacity at its input terminals (dc). The STATCOM considered here, is a voltage source inverter that produces from a given (dc) voltage, a set of three-phase ac PWM output voltage, each of which is in phase with, and coupled to the corresponding ac system via a relatively small inductance.

The construction controller of the STATCOM is used to operate the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that the STATCOM generates or absorbs the desired var at the point of connection [5–7] .

Referring to Fig. 1, if the inverter output voltage V_C is in phase with the voltage of ac system V_S, there is no net active power flow between inverter and ac system. The quantity and the sign of reactive power depend on the magnitude of inverter output voltage. If it is higher than ac system voltage, then reactive power is supplied to the system. If it is lower, then reactive power is absorbed by converter circuit

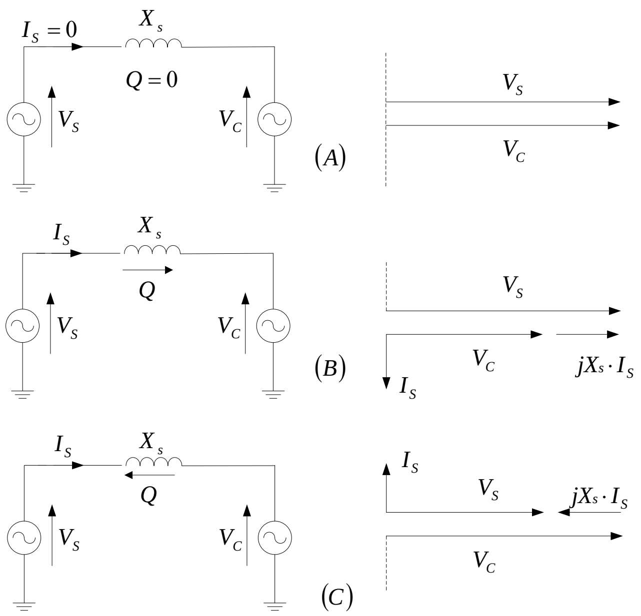

Fig. 1 – Operation mode of STATCOM: A) no load mode; B) inductive operation; C) capacitive operation.

3. SPACE VECTOR MODULATION FOR FIVE LEVEL NEUTRAL POINT CLAMPED CONVERTER

Figure 2 shows a five-level neutral point clamped converter in which the dc bus consists of four capacitors, C_1, C_2, C_3, and C_4 . For dc bus voltage V_{dc}, the voltage across each capacitor is $V_{dc}/4$, and each device voltage stress will be limited to one capacitor voltage level $V_{dc}/4$ through clamping diodes. To explain how the staircase voltage is synthesized, the neutral point n is considered as the output phase voltage reference point. There are five switch combinations to synthesize five level voltages across *a* and *n* [3, 5, 7].

For voltage level $V_{an} = V_{dc}/2$, turn on all upper switches $S_1 - S_4$.

For voltage level $V_{an} = V_{dc}/4$, turn on three upper switches $S_2 - S_4$ and one lower switch $S_1^{'}$.

For voltage level $V_{an} = 0$, turn on two upper switches S_3 and S_4 and two lower switches $S_1^{'}$ and $S_2^{'}$.

For voltage level $V_{an} = -V_{dc}/4$, turn on one upper switch S_4 and three lower switches $S_1^{'}$ to $S_3^{'}$.

For voltage level $V_{an} = V_{dc}/2$, turn on all lower switches $S_1^{'}$ to $S_4^{'}$.

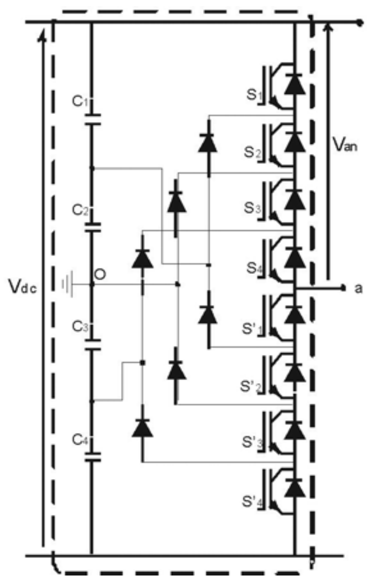

Fig. 2 – One phase of neutral point clamped multilevel inverter. (Five level).

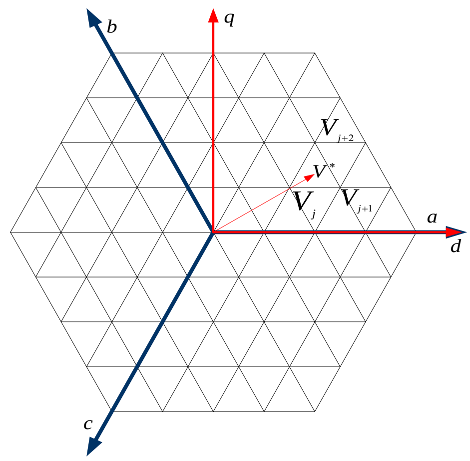

Fig. 3 – Space-vector diagram for five-level inverter.

Space vector modulation is a technique where the reference voltage is represented as a reference vector to be generated by the power converter. So, SVM identifies each switching state of a multilevel inverter as a point in complex $(\mathrm{d,q})$ space. Figure 3 shows space vectors for the five-level inverters. The adjacent three vectors can synthesize a desired voltage vector by computing the duty cycle $(T_j,\ T_{j+1}$ and $T_{j+2})$ for each vector:

$$V^* = \frac{(T_j V_j + T_{j+1} V_{j+1} + T_{j+2} V_{j+2})}{T}. \tag{1}$$

Space-vector PWM methods generally have the following features: good utilization of dc link voltage, low current ripple, and relatively easy hardware implementation by a digital signal processor (DSP). These features make it suitable for high-voltage high-power applications. This paper investigates neutral clamped multilevel inverter and its application in reactive power compensation. More detailed explanation and proof of all statements can be found in [1, 3, 5, 8].

4. **SYSTEM MODELING**

Figure 4 shows the equivalent circuit of a converter connected as a STATCOM, where V_{sabc} are the inverter ac side phase voltages and V_{Cabc} are the system-side phase voltages, i_{abc} are the phase currents. After applying Kirchhoff's voltage law to this circuit, the equations to synchronous orthogonal *d*-*q* frame, a direct relationship between input and output is achieved. That would be described below.

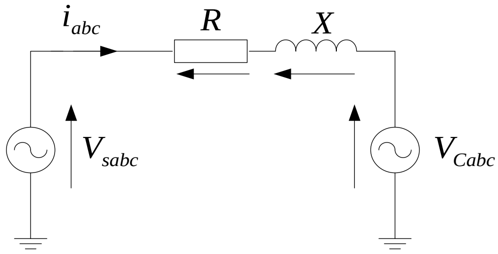

Fig. 4 – Equivalent circuit of the STATCOM.

At first, the three-phase current equations can be written as follows:

$$\begin{gathered} L\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} - \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} V_{dc} , \\ C\frac{\mathrm{d}V_{dc}}{\mathrm{d}t} = S_a i_a + S_b i_b + S_c i_c - i_{load} , \end{gathered} \tag{2}$$

omitting the high frequency component V_{Ca}, V_{Cb}, V_{Cc} to present the VSC output voltage:

$$L\frac{\mathrm{d}i_{abc}}{\mathrm{d}t} = -Ri_{abc} + V_{sabc} - V_{Cabc} . \tag{3}$$

Equations (2) can be transferred to synchronously rotating *d*-*q* reference frame as follows:

$$\begin{gathered} V_{sd} = Ri_d + L\frac{\mathrm{d}i_d}{\mathrm{d}t} - \omega L i_q + V_{Cd} \\ V_{sq} = Ri_q + L\frac{\mathrm{d}i_q}{\mathrm{d}t} - \omega L i_d + V_{Cq} \\ C\frac{\mathrm{d}u_{dc}}{\mathrm{d}t} = \frac{3}{2}(S_d i_d + S_q i_q) - i_{load} \end{gathered} . \tag{4}$$

5. **STATCOM CONTROL STRATEGY**

Figure 5 show an overview diagram of the STATCOM control system and its interface with the main circuit [2, 9, 10].

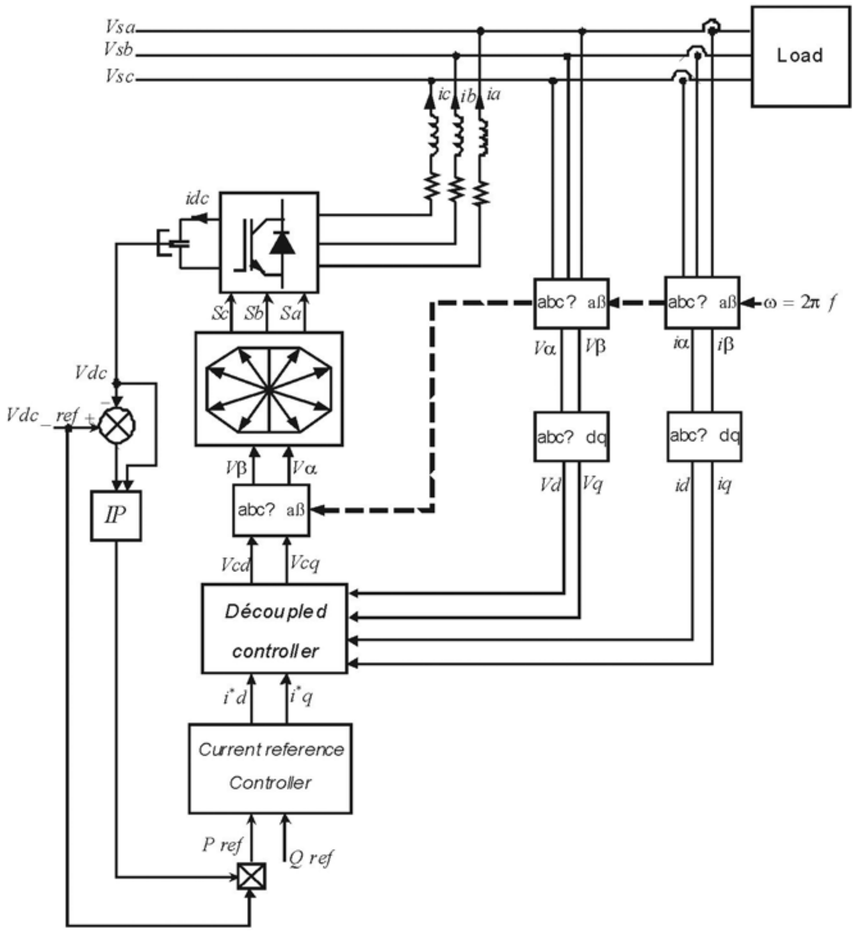

Fig. 5 – Block diagram of the proposed control strategy.

5.1. CONTROL OF REACTIVE POWER

It is well known that the amount and type (capacitive or inductive) of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage. The reactive power supplied by the STATCOM is given by:

$$Q = \frac{V_C - V_s}{X_S} V_s \,, \tag{5}$$

where V_C and V_s are the magnitudes of STATCOM output voltage and system voltage, respectively, and X_S is the equivalent impedance between STATCOM and the system.

When Q is positive, the STATCOM supplies reactive power to the system. Otherwise, the STATCOM absorbs reactive power from the system. As a result, the reactive power requirement of the consumer or the difference between the STATCOM power and the load reactive power are then compared with Q_{ref}, which is the additional reactive power to be generated or absorbed by the STATCOM system. [2, 6, 11] . We note that The decoupled d axis component i_d and q axis component i_q are regulated by two separate IP regulators. The instantaneous i_d reference and the instantaneous i_q reference are obtained by the control of the dc voltage and the ac terminal voltage measured. Thus, instantaneous current tracking control is achieved using four IP regulators. Now, assume that the STATCOM output voltage is determined by the following IP controller:

$$\begin{cases} V_{Cq} = \left[\left(\dfrac{k_{iq}}{p} \right) k_{pq} \left(i_q^* - i_q \right) \right] - \omega L i_d + V_{sq} \\ V_{Cd} = \left[\left(\dfrac{k_{id}}{p} \right) k_{pd} \left(i_d^* - i_d \right) \right] + \omega L i_q + V_{sd} \,. \end{cases} \tag{6}$$

5.2. CONTROL OF DC CAPACITOR VOLTAGES

If all the components in Fig. 4 were ideal and the STATCOM output voltage were exactly in phase with the system voltage, there would have been no real power exchange between the STATCOM and the system. Therefore, the voltages across the dc capacitors would have been able to sustain.

However, a slight phase difference between the system voltage and the STATCOM output voltage is always needed to supply a small amount of real power to the STATCOM to compensate the component loss, so that the dc capacitor voltages can be maintained. This slight phase difference is achieved by adjusting the phase angle of the sinusoidal modulating signal.

If the real power delivered to the STATCOM is more than its total component loss, the dc capacitor voltage will rise, and vice versa. The real power exchange between the STATCOM and the system is described by:

$$P = \frac{V_s V_C}{X_S} \sin(\delta) \,, \tag{7}$$

where δ is the phase angle difference between STATCOM voltage and the system voltage. IP controller presented is adopted to regulate and equalize the dc capacitor voltage. The basic idea of this controller is to use the error between the reference and the actual dc voltage as feedback signal. This signal is then fed to an IP regulator to produce the phase angle to control the real power exchange between the STATCOM and the system and, thus, regulate the dc capacitor voltage.

6. SIMULATIONS STUDIES

To validate the operation of the STATCOM, a five level neutral clamped inverter using SVM modulation was simulated using the Matlab Program. The test system is a simple power system 2300 V network grid equipped with a ±200 kvar STATCOM and its IP controller which connected with the transmission system. The main parameters are as follows:

Load parameters: per phase load specification for delta connected load is as follows: $R = 0.1\ \Omega$, $L = 0.5$ mH.

IP controllers parameters. $K_{pd} = 20$, $K_{id} = 180$, $K_{pV} = 0.05$, $K_{iV} = 21$.

System parameters. Phase voltage $V_s = 2\ 300$ V rms/ phase, frequency $f_s =$ 50 Hz, reactive power transmitted= ± 200 kvar, PWM modulation frequency = 1.25 kHz, dc voltage source (V_{dc})= 4 300 V, $C_{dc} = 1\ 000\ \mu$F.

The phase voltage and harmonic spectral of phase voltage is shown in Fig. 6A and B. From harmonic spectra of phase voltage, it can be clearly seen a little distortion with a THD of 12.54% (Fig. 6A), also in Fig. 6B, ac response of the first phase of the STATCOM [12].

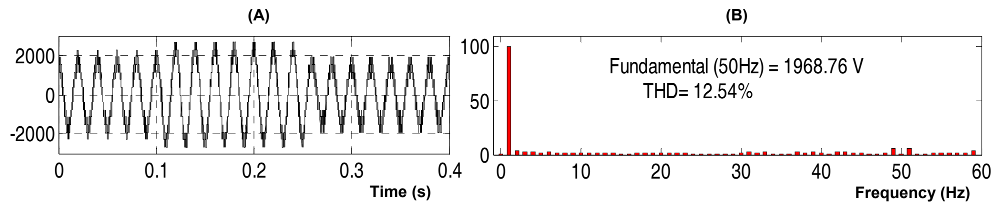

Fig. 6 – A) Converter output voltage (volt); B) harmonic content from the first phase of the compensator.

From Fig. 7A, it can be seen at 0.1s, the STATCOM behaves as a capacitor producing leading currents (The inverter phase currents are leading the inverter voltage for 90 degrees). At 0.25 s, the STATCOM behaves as an inductor producing lagging currents (The inverter phase currents are lagging the inverter voltage for 90 degrees). Figure 7B shows the active power trajectory. It can be seen that a small amount of real power is consumed by STATCOM to compensate the component loss. in the same figure we shows the dynamic response of reactive power, at 0.25 s when the reactive power of the STATCOM turns from realeasing 200 kvar to absorbing 200 kvar.

Figure 7C shows dc voltage regulation, where only small deviations are observed. These deviations are smaller than 17%, and they take less than 50ms. In the same figure the dc bus current.

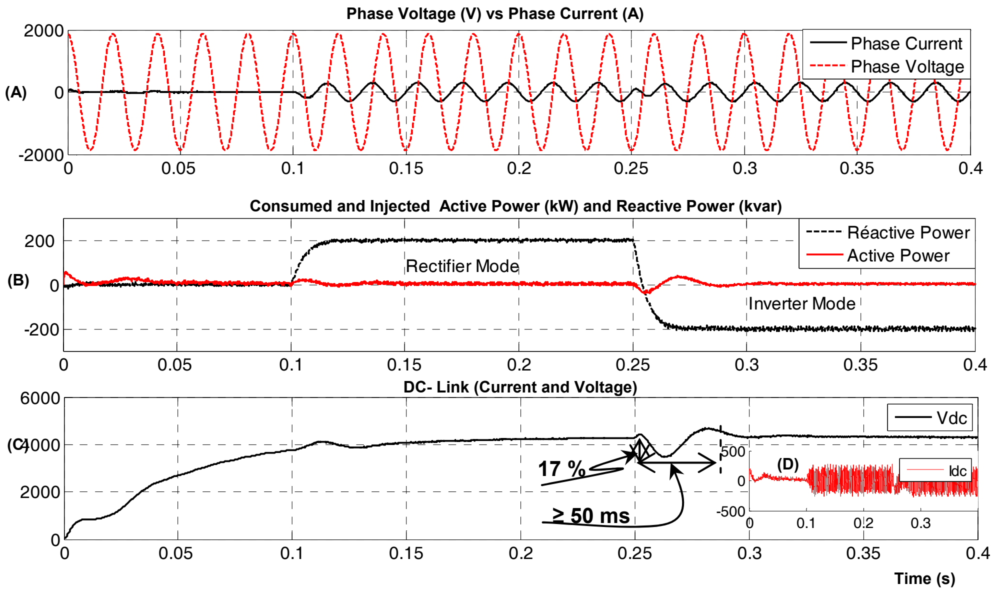

Fig. 7 – A) Phase current [ampere], phase voltage [volt]; B) active and reactive power [watt] and kvar; C) dc link voltage [volt]; D) dc current [ampere].

7. CONCLUSION

The main topic of this paper was to analyze and to simulate the neutral point clamped multilevel inverter controlled by SVM and its application as STATCOM. The mathematical models of the main components were presented. Since the control strategies implement decoupled current control with IP controllers to ensure fast controllability, minimum oscillatory behavior.

All simulation studies were developed using MATLAB and confirm that the controller improve responses keeping its stablity against all parameters variations and uncertainties.

Finally it can be seen that the switching between the three modes are very smooth. we find also that the STATCOM takes almost no time to achieve the changeover. This simulation result further demonstrates the extremely fast dynamic response of the proposed STATCOM.

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