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Performance improvement usig three-level neutral point clamped statcom performances using robust controllers

Abstract*. This paper deals with multilevel Neutral Point Clamped (NPC) inverter applied as STATCOM. The proposed control with Space Vector Modulation (SVPWM) switching and decoupled current control with (IP) controllers have been tested to prove the advantages of the proposed control. In order to ensure fast and stable voltage regulation, reduced switching Losses and minimizing harmonic voltage under all operating conditions, we focused in this study on design and implantation of sliding mode controller for Statcom. The simulation has shown the improved performance of the proposed controller with effectiveness and efficiency results compared with the conventional IP controller.*

Streszczenie*.* Artykuł dotyczy wielopoziomowego falownika z zaciskiem punktu neutralnego (NPC) stosowanego jako STATCOM. Proponowane *sterowanie z przełączaniem modulacji wektora przestrzennego (SVPWM) i sterowanie prądem odsprzężonym za pomocą sterowników (IP) zostało przetestowane w celu udowodnienia zalet proponowanego sterowania. W celu zapewnienia szybkiej i stabilnej regulacji napięcia, zmniejszenia strat przełączania i zminimalizowania napięcia harmonicznych we wszystkich warunkach pracy, skupiliśmy się w tym badaniu na projektowaniu i wdrożeniu regulatora trybu ślizgowego dla Statcom. Symulacja wykazała lepszą wydajność proponowanego sterownika z wynikami skuteczności i wydajności w porównaniu z konwencjonalnym sterownikiem IP.* (***Poprawa wydajności dzięki trójpoziomowym statcom z zaciskiem punktu neutralnego przy użyciu solidnych kontrolerów***)

Keywords: Statcom, Neutral Point Clamped inverter, IP controller, Space Vector Modulation, Sliding Mode controller, Reactive power.
Słowa kluczowe: Statcom, punkt neutralny, sterownik IP

Introduction

In a power distribution system, voltage disturbance contributes more than 80% of power quality (PQ) problems that exist in power systems. It is caused by a fault in the utility system, a fault within the customer's facility or a large increase of the load current, like starting a motor or transformer energizing, operation of process controllers.

STATCOM (static synchronous compensator) based on multilevel inverter is considered for this application, because it provides many advantages, in particular the fast response time and superior voltage support capability with its nature of voltage source. Controlled reactive power sources are commonly used for load voltage regulation in presence of disturbances like voltage sag.

In this study the STATCOM employs, is a solid state switching inverter 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 construction controller of the STATCOM based on multilevel inverter 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 [1] [2] [3].If the inverter output voltage is in phase with the voltage of ac system, 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 inverter circuit.

To ensure the stable operation of STATCOM based on multilevel inverter topology, many research works about its control strategy have been carried out [4]. Conventional controllers for instance are usually designed to have fast response and adequate stability margin at the weakest network condition. For example, the IP controllers are simples, and very practical, otherwise the most widely used in the process industry. However, the controller gains are determined under a particular operating condition and may become completely unsatisfactory for another [3], due to satisfactory performance under a wide range of operating conditions, sliding mode control (SMC) has gained much attention for its robustness compared of conventional controllers.

In order to ensure the fast response time and a robust against all parameter uncertainties, this paper examines a robust controller for STATCOM based on Sliding Mode Method compared with conventional IP controllers. The remainder of this paper is organized as follows. First part ,the compensator power structure is presented in section II, and the gating and control strategies are described in section III, the modeling and control structure for reactive power is explained in section IV by simulation in Simulink/ Matlab. In the second part the dynamic model of power system and SMC controller design are depicted with dynamic simulations works still in Simulink/ Matlab. Finally conclusions are drawn in section V.

SVM Modulation for three Level NPC inverter

Figure 1 illustrates the fundamental building block of a Neutral Point Clamped inverter. The dc-bus voltage is split into three level by two series-connected bulk capacitors, C_1 and C_2. The middle point of the two capacitors n can be defined as the neutral point. The inverter in Figure 1 provides a three-level output across a and n.

For voltage level $V_{dc}/2$, switches S_{11} and S_{21} need to be turned 'ON'.

For $-V_{dc}/2$switches S_{11} and S_{21} need to be turned 'ON'; and for the '0' level, either pair (S_{21}, S_{11}) needs to be turned 'ON'.

The same switching pattern applies across the phase 'b' leg (if 'a' is replaced by 'b') but phase shifted by 180° for the single phase configuration (in the three-phase configuration the shifts between the phases will be 120˚) [5] [6] [17] [19].

Space Vector Modulation is a technique where the reference voltage is represented as a reference vector to be generated by the power inverter. So, SVM identifies each switching state of a multilevel inverter as a point in complex

(d,q)space. Figure 2 shows space vectors for the three-level inverter. The adjacent three vectors can synthesize a desired voltage vector by computing the duty cycle $\left(T_j, T_{j+1} \text{ and } T_{j+2}\right)$ for each vector [7] [8] [9]:

(1) $V^* = \dfrac{\left(T_j V_j + T_{j+1} V_{j+1} + T_{j+2} V_{j+2}\right)}{T}$

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 Point Clamped multilevel inverter and its application in reactive power compensation. More detailed explanation and proof of all statements can be found in [9] [10].

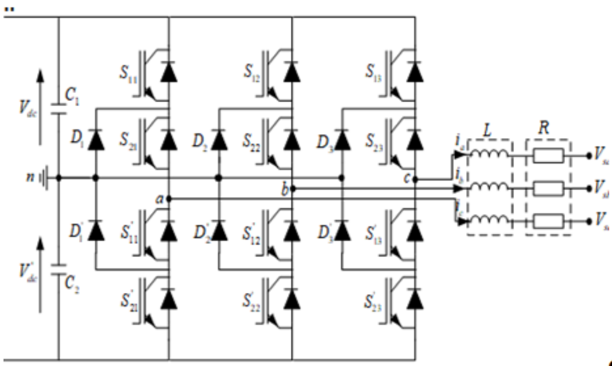

Fig.1. Basic Model of VSC (Three-Level Neutral Point Clamped inverter circuit topology).

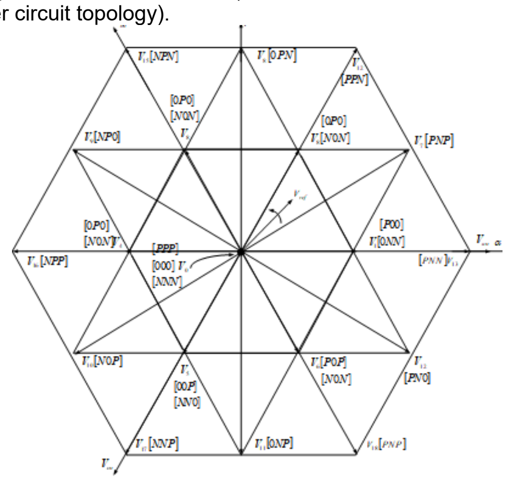

Fig. 2. Space-vector diagram for three-level inverter.

System Modelling

Figure 3 shows a three-cell three-level Neutral Point Clamped inverter connected to a three-phase load. The line-to-neutral voltage of the three phases can be expressed as:

(2) $v_{xn} = \dfrac{S_x}{3} V_{dc}$ with Sx=0,1,…3.

Where x represents the phase a, b, or c, and Sx represents the phase switching states selected by the gating signals [11] [21].

Also we shows the equivalent circuit of a inverter connected as a STATCOM, where V_{sabc} are the inverter ac side phase voltages andV_{Cabc} are the system-side phase voltages, i_{abc} are the phase currents.

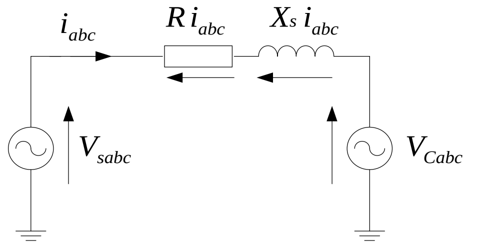

Figure 3. Equivalent circuit of the STATCOM.

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

$$(3)\quad L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} - \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} V_{dc}$$

$$C\frac{dV_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_{load}$$

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

(4) $L\dfrac{di_{abc}}{dt} = -Ri_{abc} + V_{sabc} - V_{Cabc}$

Equations (4) can be transferred to synchronously rotating d-q reference frame as follows [16] [18]:

$$V_{sd} = Ri_d + L\frac{di_d}{dt} - \omega L i_q + V_{Cd}$$

$$(5)\quad V_{sq} = Ri_q + L\frac{di_q}{dt} - \omega L i_d + V_{Cq}$$

$$C\frac{du_{dc}}{dt} = \frac{3}{2}(S_d i_d + S_q i_q) - i_{load}$$

STATCOM Control Strategy

Figure 4 show an overview diagram of the STATCOM control system and its interface with the main circuit.

Decoupled Current Control (p-q theory)

The decoupled d axis component id and q axis component iq are regulated by two separate IP regulators. The instantaneous id reference and the instantaneous iq 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 [16]:

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

The decoupled control system is implemented as shown in Figure 5.

Using the definition of the instantaneous reactive power theory for a balanced three phase three wire system, the quadrature component of the voltage is always zero The real (P) and the reactive power (Q) injected into the system by the STATCOM can be expressed under the dq reference frame:

$$(7)\quad \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_{sd} & V_{sq} \\ -V_{sq} & V_{sd} \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

In dq frame, $V_{sd} = V_{moy}$, $V_{sq} = 0$, id and iq completely describe the instantaneous value of real and reactive powers produced by the STATCOM when the system voltage remains constant. Therefore the instantaneous three phase current measured is transformed by abc to dqo transformation.

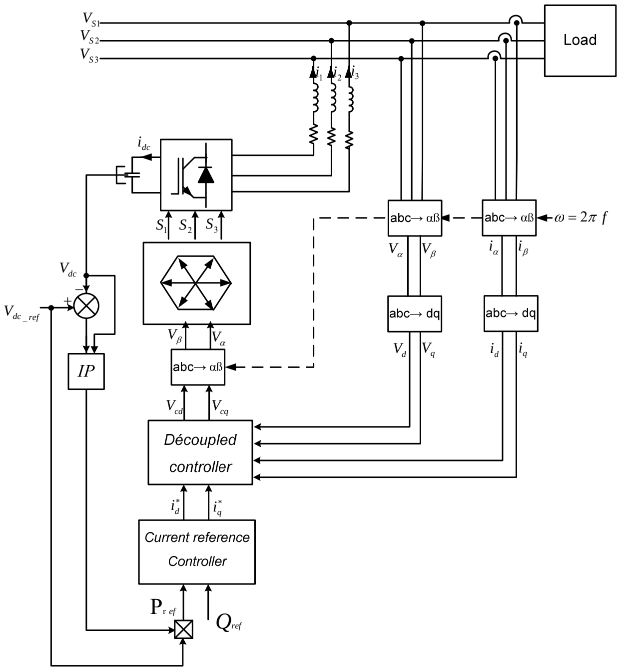

Fig. 4. Block diagram of the proposed control strategy.

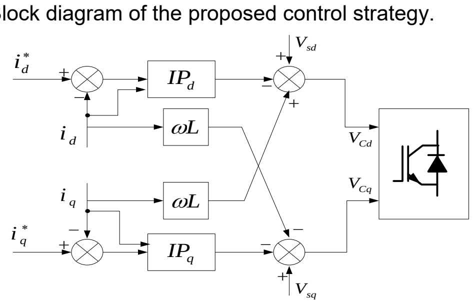

Fig.5. Decoupled Controller.

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:

$$(8)\quad Q = \frac{V_C - V_s}{X} V_s$$

where V_C and V_s are the magnitudes of STATCOM output voltage and system voltage, respectively, and Xs 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 Qref, which is the additional reactive power to be generated or absorbed by the STATCOM system. The error signal is evaluated using an IP control system which is shown in Figures 4 and 5 [12].

Control of DC Capacitor Voltages

If all the components in Figure 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:

$$(9)\quad P = \frac{V_s V_C}{X}\sin(\delta)$$

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.

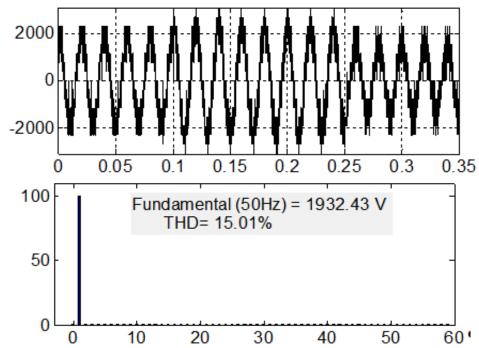

Figure 6.a) Inverter output voltage [volts], b) Harmonic content from the first phase of the compensator

. Simulations results with IP regulator

To validate the operation of the STATCOM, a three level Neutral Point 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 Ω, L=0.5 mH.

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

System parameters: Phase voltage $V_S = 2300\,V$ rms/ phase, frequency $f_S = 50\,Hz$, reactive power transmitted =

± 200 kvar, PWM modulation frequency = 1.25 kHz, dc voltage source $V_{dc} = 4300\,V$, $C_{dc} = 1000\,\mu F$.

The phase voltage and harmonic spectral of phase voltage is shown in figure 6.a-b. From harmonic spectra of phase voltage, it can be clearly seen a little distortion with a THD of 15 % (figure 6.a), also in figure 6b, ac response of the first phase of the STATCOM [13].

From figure. 7.a, 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 0.25s, the STATCOM behaves as an inductor producing lagging currents (The inverter phase currents are lagging the inverter voltage for 90 degrees). Figure.7.b 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 0.25s when the reactive power of the STATCOM turns from releasing 200 kVar to absorbing 200 kVar.

Figure. 7.c 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.

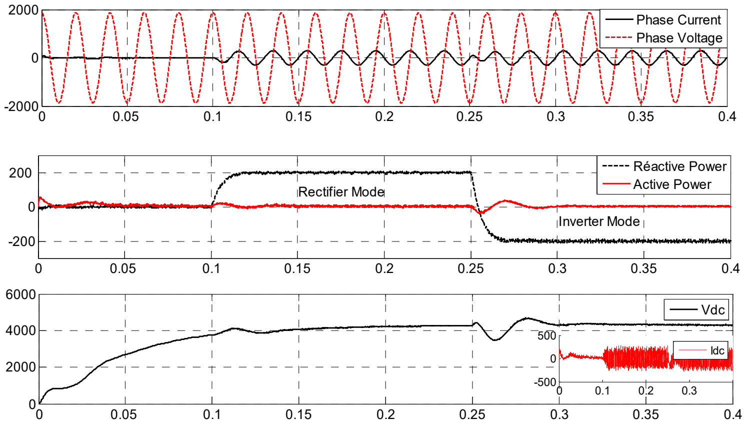

Figure 7.a) Phase Current [Ampers], Phase Voltage [volts], b) Active And Reactive Power [watts], c) DC Link Voltage [volts], d) DC Current [Ampers].

Sliding mode controller

Assuming that the dynamics of the DC bus voltage is mach slower than that of the AC currents, the value of V_{dc} in each simple period can be considered constant. Then the states of the input variable of the system are: [6] [7] [8]

(10) $U = [x_1, x_2]^T = [V_{sq}, V_{sd}]^T$

Then the output variables:

(11) $Y = [u_1, u_2]^T = [i_q, i_d]^T$

So the inverter system expression of compensator mathematical model can be got as equation (7):

(12) $\dot{X} = f(X,U)\begin{cases} \dot{i}_d = -\frac{R}{L} i_d + \omega i_q + \frac{1}{L}\left(V_{sd} - V_{Cd}\right) \\ \dot{i}_q = -\frac{R}{L} i_q - \omega i_d + \frac{1}{L}\left(V_{sq} - V_{Cq}\right) \end{cases}$

Currents Régulation

Id Régulation

The following tracking errors can be described as follows:

(13) $e\left(i_d\right) = i_{dref} - i_d$

Based on Slotine equation, the sliding mode switching surface can be obtained by:

(14) $S\left(i_d\right) = \left(\frac{\partial}{\partial t} + \lambda_x\right)^{r-1} e\left(i_d\right)$

(15) $S\left(i_d\right) = e\left(i_d\right)$ with r=1.

(16) $S\left(i_d\right) = i_{dref} - i_d$

Used (11) with respect to time (t) and take equation (7) respectively, yields:

(17) $\dot{S}\left(i_d\right) = \dot{i}_{dref} - \dot{i}_d$

(18) $\dot{S}\left(i_d\right) = \dot{i}_{dref} + \frac{R}{L} i_d - \omega i_q - \frac{1}{L}\left(V_{sd} - V_{cd}\right)$

During the sliding mode and in permanent regime, we have:

$S\left(i_d\right) = 0$, $\dot{S}\left(i_d\right) = 0$, $V_{sdn} = 0$ where the equivalent control is

(19) $V_{sdeq} = -L\omega i_q + R i_d + L\dot{i}_{dref} + V_{cd}$

During the convergence mode, the condition $\dot{S}\left(i_d\right) S\left(i_d\right) < 0$ must be verified.

We remplace equation (15) in equation (14) we obtain:

(20) $\dot{S}\left(i_d\right) = -\frac{1}{L} V_{sdn}$

Therefore, the correction factor is given by:

(21) $V_{sdn} = k_d \; sign\left(S\left(i_d\right)\right)$

To verify the system stability condition, the parameter k_d must be positive.

Iq Régulation

Assuming that the following Sliding mode switching surface $S(i_q)$:

(22) $S\left(i_q\right) = i_{qref} - i_q$

(23) $\dot{S}\left(i_q\right) = \dot{i}_{qref} - \dot{i}_q$

(24) $\dot{S}\left(i_q\right) = \dot{i}_{qref} - \frac{R}{L} i_q + \omega i_d - \frac{1}{L} V_{sq} + \frac{1}{L} V_{cq}$

We take:

(25) $V_{sq}^* = V_{sqeq} + V_{sqn}$

(26) $\dot{S}(i_q) = \dot{i}_{qref} - \frac{R}{L} i_q + \omega i_d - \frac{1}{L}(V_{sqeq} + V_{sqn}) + \frac{1}{L} V_{cq}$

During the sliding mode and in permanent regime, we have $S(i_d) = 0$, $\dot{S}(i_d) = 0$, $V_{sqn} = 0$ where the equivalent control is:

(27) $V_{sqeq} = L\dot{i}_{qref} - Ri_q + \omega L i_d + V_{cq}$

During the convergence mode, the condition $\dot{S}(i_d) S(i_d) < 0$ must be verified.

We obtain:

(28) $\dot{S}(i_q) = -\frac{1}{L} V_{sqn}$

To verify the system stability condition, the parameter k_q must be positive.

When k_d and k_q are constants positive, The coefficient k_d is imposed in such that we have a fast dynamic response of the proposed system, also k_q is implemented in order to have a dynamic response of the system the more stable as possible.

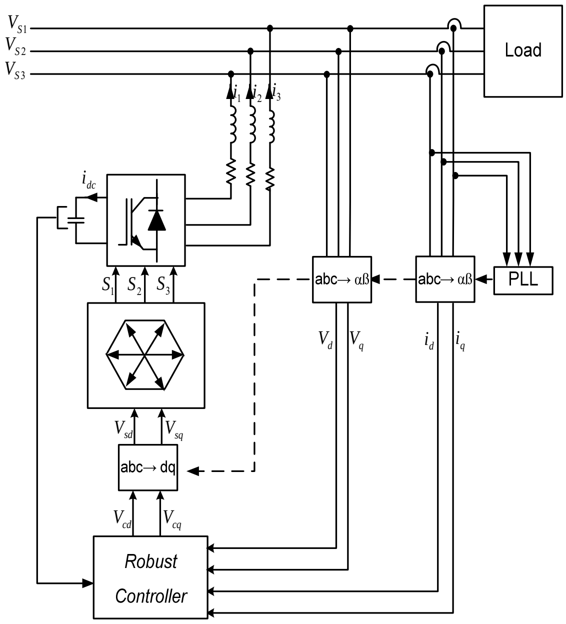

Figure8. Block diagram of the proposed control strategy.

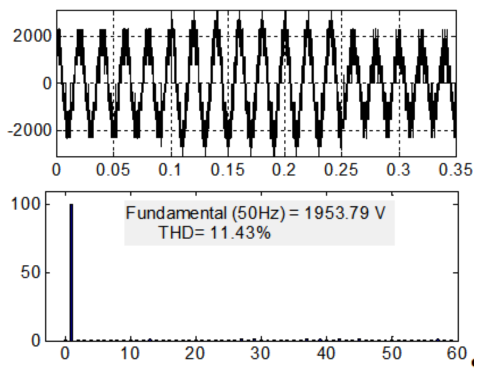

Figure 9 .a) Inverter output voltage [volts], b) Harmonic content from the first phase of the compensator

Simulations results and discussion

In order to validate the mathematical analysis and, hence, to establish the effectiveness of the proposed control scheme, simulations works are carried out for the STATCOM used a three level Neutral Point Clamped inverter using SVPWM modulation, will keeping the same parameters such as the last system. Figure 8 show an overview diagram of the STATCOM with SMC Controllers [22], [23] , [24].

Figure 9-a Illustrate the first phase of the STATCOM, also from figure 6-b it can be seen the harmonic spectra of same phase with remarkable progression of THD (11.31%)..

The figure 10 show the simulation results with classical IP control system and Sliding Mode Control of system, the figure 10.a show the reactive power simulation results and the figure 10.b show the Active power simulation results. When the STATCOM turns from releasing 200 kVar at 0.1s to absorbing 200 kVar at 0.25s, we can see that the reactive power with sliding mode controller reaches its reference within 1,5 ms, but the grid voltage with IP controller reaches its reference take longer time to recover (about 70 ms) [9] [10]. It can be seen from figure 10.b, active power also have a good rising and settling time (Ts) with sliding mode controller than the classical IP controller. Additionally, the responses of the sliding mode control can provide good damping to the oscillatory of the system. From figure 10.c, 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 0.25s, the STATCOM behaves as an inductor producing lagging currents (The inverter phase currents are lagging the inverter voltage for 90 degrees). Here we note that the phase current changes quickly with sliding mode control compared with classical IP controller. Finally the DC-Link voltage in figure 6-D, who is relatively stable with small fluctuation. Above of all, as can be seen that with sliding mode controller provides good damping to the oscillatory of the system, active power and reactive power can be stabilized very soon, and DC- link voltage is regulated to its first failure value very quickly. It is quite evident that the proposed controller achieves good transient stability and voltage regulation than classical IP control system. The simulation results show that the control method in this paper has good dynamic stability.

Conclusion

This work reveals that there has been a significant increase in interest of STATCOM and its control methods. A sliding mode controller has been designed in this paper for control of a Capacitor-clamped three level inverter with SVM technical and its application as STATCOM. Performance of the propose model and the controller design are verified by using computer simulation performed in SIMULINK/MATLAB. The simulation results show that the STATCOM with proposed sliding mode controller can be switching between the three modes rapidly, we find also that the STATCOM takes almost no time to achieve the changeover comparing with the classical IP controller system, it's clear that the proposed sliding mode controller is more effective and more stable for damping the variation of the system. Finally I would add that in this work the report (robustness - price) was able to verify because with three level a converter we did get best results compared with another of five level that automatically more expensive.

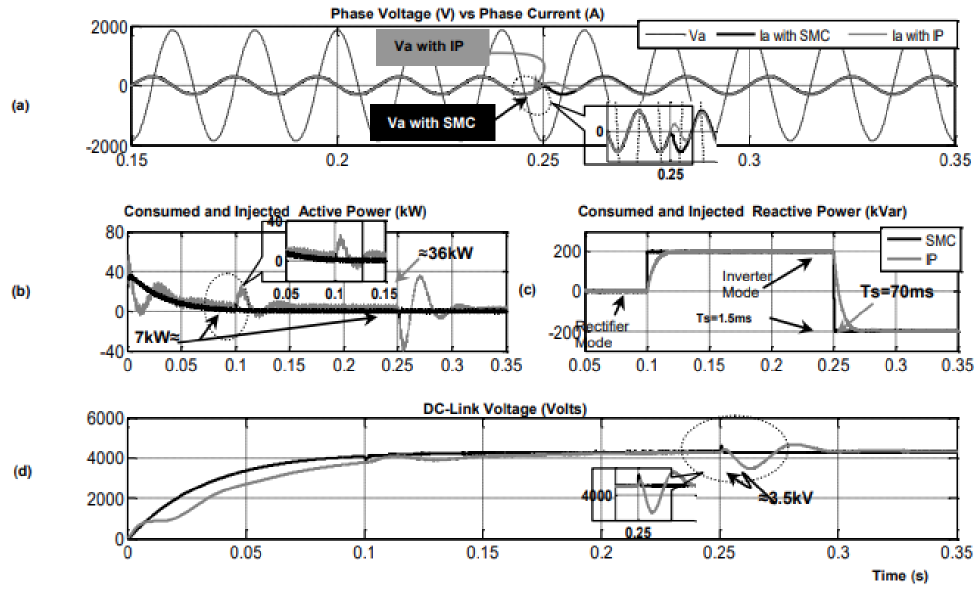

Figure 10 . a) Phase Current [Ampers] & Phase Voltage [Volts], b) Active Power [Watts], c) Reactive Power [kVar], d) DC Link Voltage [Volts].

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