REACTIVE POWER COMPENSATION with FIVE LEVEL BASED INVERTER

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Abstract: *The reactive power compensation is essential for the faultless functioning of the power system. The compensation can be performed by preserving appropriate equilibrium between generation and absorption of reactive power. STATCOM is a FACTS device family member; it is used for shunt power system compensation. This paper focus on the investigation of five levels inverter based STATCOM. The three phases STATCOM connected to one line power system is modeled and analyzed using PARK's transformation. The control structure comprises the power system and STATCOM including DC and AC characteristics. Simulation results performed on simulink/matlab program are investigated and presented.*

Key words: *STATCOM, five level inverter, reactive power compensation, diode clamped inverter.*

1. Introduction

It is well established that the shunt compensation of the reactive power is a requirement in modern power systems, which feed several types of industrial loads most of them are sensitive to the voltage variation. The compensation allows ensuring a good quality of energy and preserving a constant voltage profile for all the loads connected to the network [1].

In this context, the shunt compensator STATCOM (Static Synchronous Compensator), which is a FACTS family device member based on power electronics, is used as shunt compensator. The main objective of this device is to supply instantly the necessary amount of reactive power in away to meet the operation requirement of the power system.

STATCOM is mainly built up of three phases PWM converter that converts DC power to AC power. It has been used for voltage support of AC system and power flow control [1- 3].

The voltage source converter, which is part of STATCOM generates a fundamental output voltage wave form with demanded magnitude and phase angle in synchronism with AC system which forces the reactive power exchange required for compensation. The traditional two-level inverter produces a square wave output depending on the state on/off of the switches. For a high voltage applications, a near sinusoidal AC voltage wave is required.

Different multi-level inverter topologies have been proposed. Diode clamped multi-level inverters are widely used for FACTS devices implementation [3, 4]. This multi-level topology uses diodes and capacitors to clamp voltage stress on switching devices in order to generate a wave voltage with multiple level states [5, 6]. Different methods have been used for inverters control and switching, when the number of levels is high, switching states are numerous and become difficult to handle, so the multi carrier based PWM is feasible for its simplicity [4].

In this paper we model and implement a five NPC inverter based STATCOM. A PWM control algorithm is supplied to the inverter control and a loop control based on P-Q theory applied to the STATCOM and the whole system. Simulation results and discussion are presented.

2. Fundamentals of STATCOM

The STATCOM is generally used for voltage regulation by the shunt compensation of reactive power. It is built-up on DC to AC voltage converter to realize DC-AC power conversion Fig.1. This converter (VSC) is linked to the transmission line through a step-down transformer and a storage capacitor which can absorbs or supplies reactive to AC system [2- 4, 7, 8].

STATCOM regulates voltage by controlling the amplitude and phase angle of three phases current flowing through the AC side of the STATCOM. When this current leads the voltage across the AC side of STATCOM by 90° the STATCOM acts as an inductor and absorbs reactive power from the AC power system. The STATCOM supplies reactive power to the AC system. And when the current flowing through its AC side lags AC side voltage by 90°, the STATCOM supplies reactive power to the AC system. The amount of reactive power exchanged with AC system is determined by the magnitude of the current flowing through the AC side of STATCOM [4, 9]. The main structure of STATCOM device is shown in Fig.1.

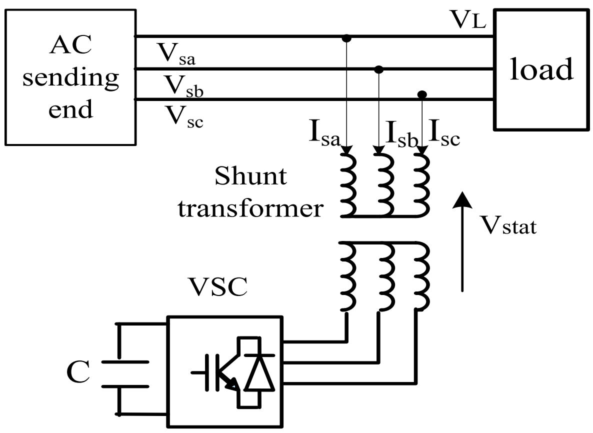

Fig.1. STATCOM's representation.

3. STATCOM modeling

Fig.2 shows the STATCOM equivalent circuit connected to one transmission line. The reactive power supplied by the STATCOM is either inductive or capacitive depending up on the relative magnitude of fundamental component of V_L with respect to V_{stat}.

The equations governing the instantaneous values of three-phase voltages across the two sides of STATCOM and the current flowing into it are given by:

$$V_{stat\,(a,b,c)} - V_{L(a,b,c)} = R_{stat\,(a,b,c)} I_{stat\,(a,b,c)} + L_{stat\,(a,b,c)} \frac{d}{dt} I_{stat\,(a,b,c)} \quad (1)$$

Where:

V $stat(a,b,c)$: output voltage inverter;

V_L: voltage at receiving end point;

I $stat(a,b,c)$: the STATCOM current.

Applying Park's transformation to the previous equation the three phases STATCOM current is presented in d-q coordinates by:

$$\frac{d}{dt} i_{stat\ d} = \frac{-R_{stat}}{L_{stat}} i_{stat\ d} + \omega i_{stat\,q} + \frac{1}{L_{stat}} (V_{L\,d} - V_{stat\ d})$$

$$\frac{d}{dt} i_{stat\ q} = \frac{-R_{stat}}{L_{stat}} i_{stat\ q} - \omega i_{stat\ d} + \frac{1}{L_{stat}} (V_{L\,q} - V_{stat\ q}) \quad (2)$$

The inverter output active and reactive power delivered to the power system (P_{stat} +jQ_{stat}) in d-q axis is given by the following equations:

$$P_{stat} = \frac{3}{2} \left(V_{stat\,d} i_{stat\,d} + V_{stat\,q} i_{stat\,q} \right) \quad (3)$$

$$Q_{stat} = \frac{3}{2} \left(V_{stat\,d} i_{stat\,d} - V_{stat\,q} i_{stat\,q} \right) \quad (4)$$

During the transient stability period, the DC capacitor will exchange energy with the AC system and consequently its voltage depends on its current inflow expressed as:

$$C \frac{d}{dt} V_{dc} = I_{dc} \quad (5)$$

Where:

I_{dc}: is the current flowing into the capacitor from the VSC.

C: is the capacitance of the capacitor.

In steady state operation the power transfer is balanced.

I_{dc}=0 and hence: $C \frac{d}{dt} V_{dc} = 0$.

Assuming that the VSC model is ideal, the DC side active power is equal to the AC instantaneous active power that is:

$$P = -V_{dc} i_{dc} = \frac{3}{2} \left(V_{stat\,d} i_{stat\,d} + V_{stat\,q} i_{stat\,q} \right) \quad (6)$$

From (5) and (6) we get:

$$\frac{d}{dt} V_{dc} = \frac{-1}{C V_{dc}} P \quad (7)$$

Equation (7) expresses the DC link dynamics.

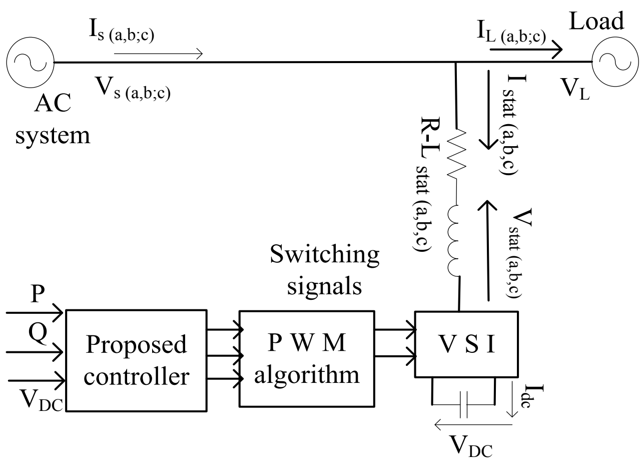

Fig.2. STATCOM's equivalent circuit.

4. STATCOM control algorithm

The control of STATCOM is based on the Principle of decoupling between the active and reactive power [4]. A closed control loop scheme is shown in Fig.3. The control concerns the regulation of the voltages DC and AC on both sides of the converter in away to maintain the voltage value near its nominal value and eliminate the DC voltage fluctuation caused by load variation.

The control is done by generating the reference currents along the two axes d-q. Reference currents are calculated from powers and measured voltages and fed PI controllers. The reference current according to the q-axis is controlled to achieve a control of the DC voltage from the variations of the power, the output which decides the amplitude of the reference of reactive current to be generated by STATCOM; the V_{DC} reference is compared to the DC link voltage and fed a PI controller, the output define the reactive power reference. Fig.3 shows the block diagram of the implemented control scheme.

The PI outputs on direct and quadrature axis are fed to carrier PWM controller which is used for tracking control. The converter switching actions are generated from a PWM multi carrier controller.

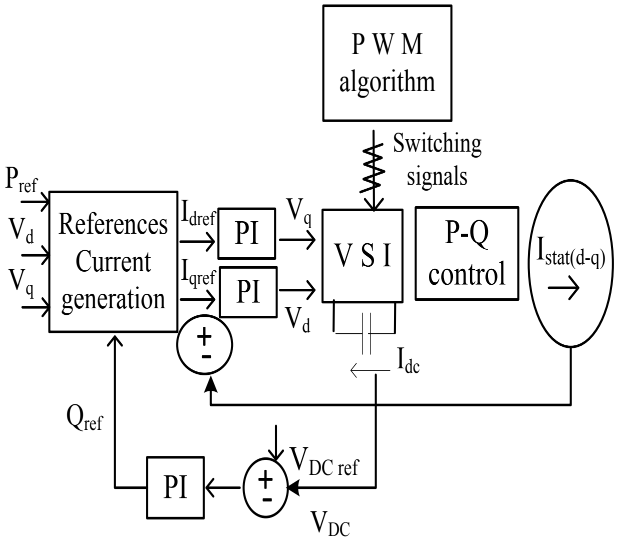

Fig.3. Control diagram of STATCOM.

5. Inverter analysis

There is a great need in use of voltage multilevel converter for higher power applications because of their capability to operate at higher output voltages. The idea, behind, is to distribute the voltage stress on many switching components placed in series [10- 12] and thereby multiply the output voltage levels. Accordingly, in this section we present the NPC five level converter structure and control when used as STATCOM compensator.

Fig.4 shows the topology of such inverter, it consist-up of clamping diodes and capacitors to produce near sin wave form voltage with multiple steps level. In this circuit the DC side is divided into four levels by four series connected capacitors. The order numbering of switches of each phase is K1, K2, K3, K4, K'1, K'2, K'3, and K'4, and ordered in pairs (K_1, K'_1), (K_2, K'_2), (K_3, K'_3), and (K_4, K'_4).

The voltage stress on each switch is limited to $V_{dc}/4$ through the clamping diodes. The middle point of the four capacitors is considered as the neutral point Fig.4. Table.1 demonstrates the output voltage and the corresponding switches states for each phase [5, 13, 14].

Table.1 Switching states and output voltage values.

K1	K2	K3	K4	K'_1	K'_2	K'_3	K'_4	Va_n
1	1	1	1	0	0	0	0	0
0	1	1	1	1	0	0	0	0
0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
0	0	0	0	0	1	1	1	1

- For voltage level V_{dC} /4 switches K2, k3 and K4 are on, K1 is Off;
- For voltage level 0 switches K3 and K4 are on, K1 and K2 are off;
- For voltage level $-V_{dC}/4$ switches K4 is on, K1, K2, K3 are off;
- For voltage level $-V_{dC}/2$ all upper switches are off.

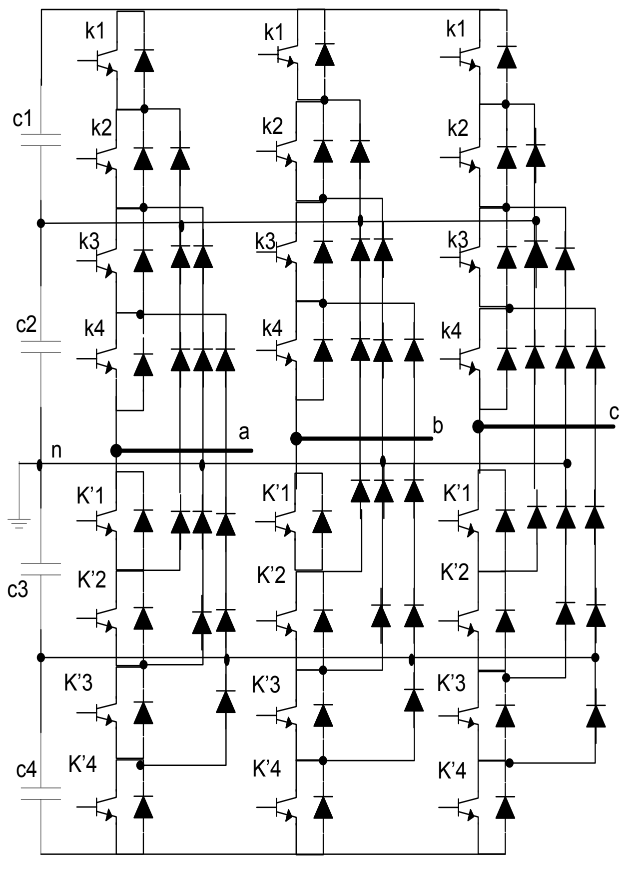

Fig.4. Five-level diode clamped inverter circuit [11].

A- Inverter control

PWM is a well known technique for two level converters. This technique has been extended for multi-level ones. The principal is to use several triangular carriers signal and one sinusoidal modulation signal Fig.5.

For an m level inverter, m-1 carriers with the same frequency f_c and same peak-to-peak amplitude A_c are disposed in such manner that the bands they occupy are contiguous [6, 10, 11]. The modulation (reference signal), waveform has peak-to-peak amplitude A_m and frequency $f_{m,}$ and it is centered in the middle of the carrier set. The modulation is continuously compared with each of the carrier signals. If the reference is greater than a carrier signal, then the corresponding device to that carrier is switched on; and if it is less than the carrier signal, then the corresponding device to that carrier is switched off. The zero reference is placed in the middle of the carriers set [7, 10, 11, 13].

B-Level- Shifted modulation

In this modulation strategy the triangular carriers are arranged one above the other and compared to the same voltage reference. Each carrier is assigned to a voltage level and the intersection with the modulating produces the generation of control orders switches to the corresponding level.

If the carriers are chosen with the same phase the method is named as phase disposition method [5, 13-15].

Fig.5 shows four carrier signals with the same frequency as (3 kHz) and a reference signal to achieve PWM. The four triangular carrier signals have the same amplitude and phase, and their DC levels are shifted appropriately.

Fig.6 shows the line to line output voltage of five-level NPC inverter controlled with multi carrier PWM method and on Fig.7 we see its line to neutral corresponding voltage.

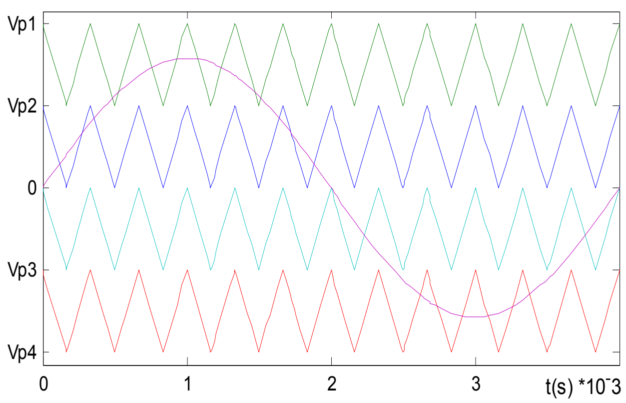

Fig.5. level shifted multi carrier sinusoidal pulse width modulation and reference wave.

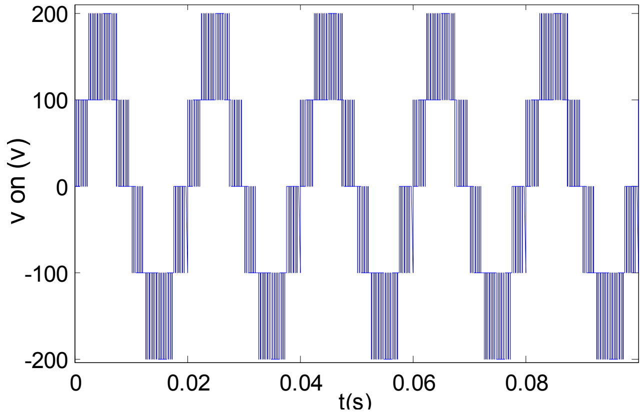

Fig.6. line to line output inerter voltage.

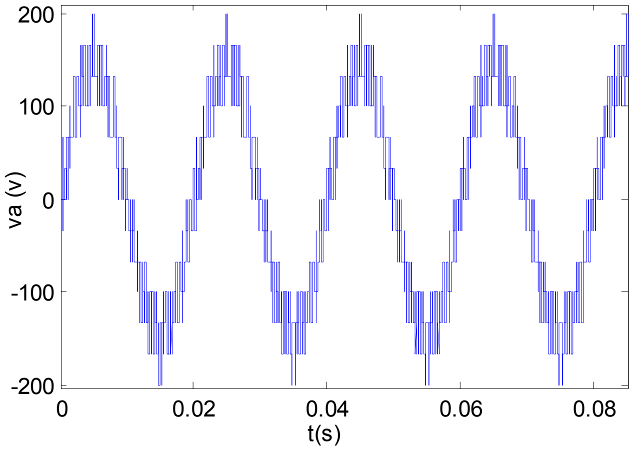

Fig.7. Five level line to neutral inverter output voltage.

6. Simulation results

The parameters used for the simulation model are listed below

Table.2 Circuit parameters of the STATCOM.

DC capacitor voltage	V_{dc}	110
DC link voltage	$4V_{dc}$	440 V
Capacitance of capacitor	C_{dc}	2000 μF
Coupling transformer resistance	R_{stat}	0.4 Ω
Transformer inductance	L_{stat}	10mH
Sending end AC system voltage	V_s	220 V
Load voltage	V_L	220
AC system frequency	f	50 H

Fig.8 shows the quasi sinusoidal phase output voltage of the inverter; Fig.9 shows Line to line waveform of the STATCOM inverter

Fig.10 shows the dynamic of reactive power. It goes from -1600 VAR the compensator supplies power to power system, to zero, at t=1.5s, then to +1600VAR the compensator absorbs power from power system at t=3s it has the same appearance as like quadrature axis current I_q.

Fig.11 shows the dynamic response of STATCOM active power it has the same appearance as well as d axes current because they are related each other.

Fig.12 and Fig.13 present the STATCOM current evolution for different load modes (capacitive, resistive and inductive)

Fig.14 presents the phase current I_a of the compensator instead AC system voltage V_{sa}, for the first change in compensator current in qudrature with the voltage V_{sa}, current leads voltage with 90°, at t=0.15s current is in phase with voltage V_{sa} (in Fig.10, resistive load), here there is no reactive power exchange. At t=0.21s another change in current, it lags voltage with 90° (inductive load), in Fig.13 i_q= +4A.

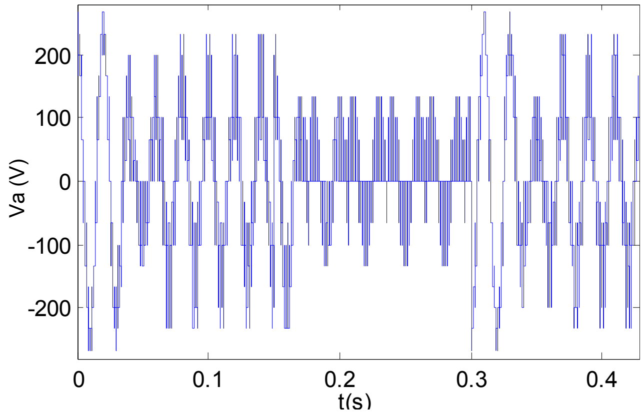

Fig.8. phase output inverter voltage.

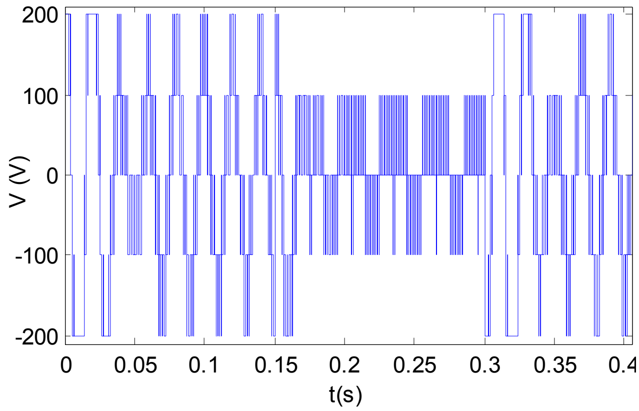

Fig.9. line to line output inverter voltage wave form.

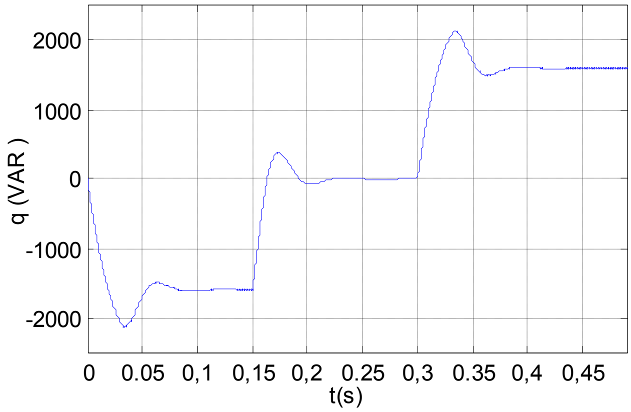

Fig.10. STATCOM's reactive power response.

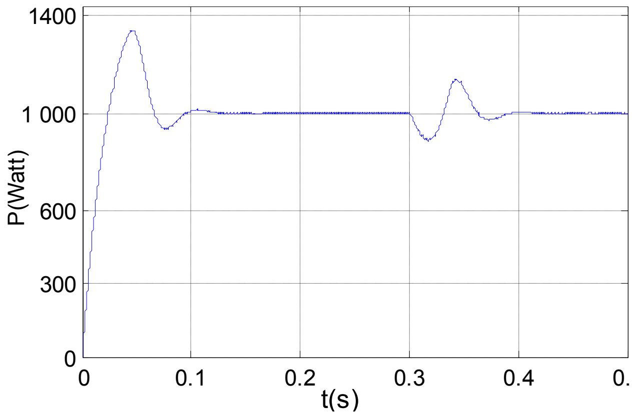

Fig.11. active power response of STATCOM.

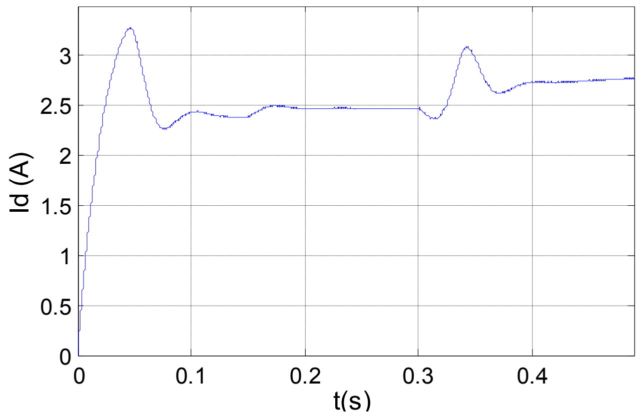

Fig.12. d- axis current response.

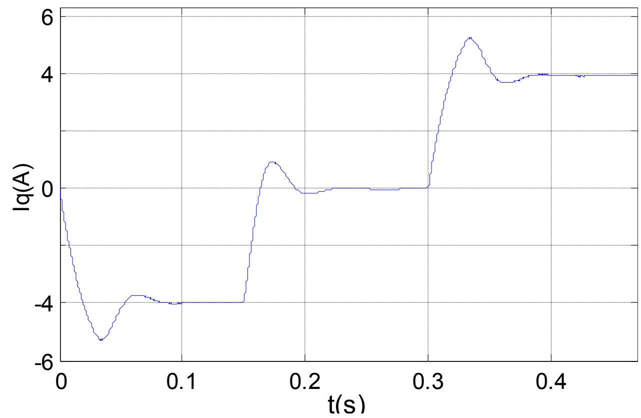

Fig.13. q- axis current response.

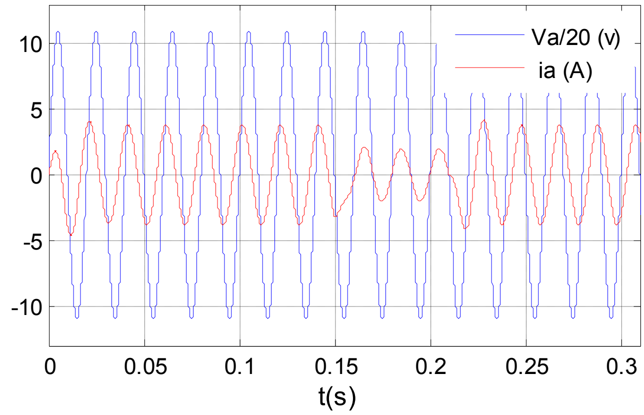

Fig.14. Sending end phase voltage and output inverter current phase.

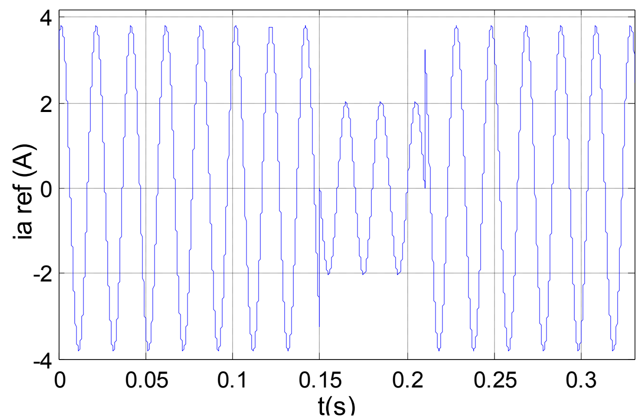

Fig.15. Reference current ia_{ref}.

7. Conclusion

Multilevel inverter-based STATCOM is modeled and simulated using SIMULINK blocks. Simulation results are presented and they are in line with the predictions.

Consequently, a reactive power compensator based on a three-phase PWM five level NPC inverter, to regulate reactive power on load grid was developed. Additionally, a control plan based on P-Q theory is described; the current references were derived on d-q reference. Also, a regulation loop for DC link was proposed to reduce non constant load perturbation.

Finally, simulation results show good dynamic performance of STATCOM with load reactive power changes.

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