International Journal of Engineering &Technology, 7 (1.8) (2018) 148-152

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

DC capacitor voltage stabilization for five-level NPC inverter based STATCOM under DC offset in load

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Abstract

DC voltage regulation of compensator plays a significant role in tracking performance of STATCOM. It is a common practice to employ voltage source inverter with split – capacitor topology for shunt compensator in three phase four wire systems. However, drift in each capacitor voltage is observed with the presence of dc component in zero sequence current although STATCOM control unit regulates total dc voltage, which results in poor tracking of reference current by the compensator. An external voltage balancing circuit is identified to be a good solution to overcome this problem. This paper proposes an improved controller for external voltage balancing circuit to restore the dc capacitors voltage. The effectiveness of the proposed control of external voltage balancing circuit is verified by simulation results showing restoration of capacitors voltage drift and there by the restoration of tracking performance of the compensator.

Keywords: *Five-Level Inverter, Harmonics, NPC inverter, STATCOM, Voltage Stabilization*

1. Introduction

The problems caused by non-linear loads and their effects on electric power system are presented in [3]. [1]- [2] proposes requirements for harmonic control, recommended practices and IEEE harmonic standards. [4]-[11] presents different topologies of shunt active power filters. The recent trends in shunt compensation are given in [4]. Different methods are available for compensation current generation both in time domain and frequency domain. [5] Proposes p-q method, [6] proposes synchronous detection method, [17],[18] proposes instantaneous symmetrical components theory for the generation of compensation current. Also other methods like simple peak detection are also available.

Current controller is another important element of shunt filter whose choice determines the reference inverter current tracking performance of the compensator. Different current control techniques such as hysteresis control [8], PI control [9], pulse width modulation [10], space vector modulation [11] are studied.

The use of multi-level inverters for shunt compensation application is presented in [12]-[18] . Multi- level inverters with their capability of handling high voltage without series connection of multiple switches, low dv/dt on switches are becoming popular for shunt compensation even at 6.6 kV. Also, with multiple voltage levels made available, tracking of compensation current is made efficient than two level inverter. Many topologies for multi-level inverter are available in literature such as diode clamped, flying capacitor, cascaded H-bridge models with their respective advantages and disadvantages. However, the first unified power flow controller (UPFC) in the world was based on a three level diode-clamped inverter [13]. Cascaded H-bridge multi-level inverters are equally good for shunt compensation application [14]. It is observed that flying capacitor topology [12] is not suitable for reactive power compensation as it cannot have balanced voltage for power conversion involving only reactive power.

A five level diode clamped inverter is considered in the present work. Capacitor voltage drift and neutral shift are the two main problems using diode clamped structure. This would be severe if zero sequence current has dc component. To address this issue, self -balancing of capacitor voltages by paralleling Capacitor- cells is proposed in [15]. An additional chopper circuit [17]-[18] for balancing capacitors voltage is a better solution. The current controller for chopper circuit could be either a hysteresis control [17] or PI controller [18]. The use of multilevel inverters for shunt compensation being the interest of present work , a five level diode clamped topology based voltage source inverter with neutral wire tied to the mid- point of four capacitors is considered as shunt active filter. The objective of the present work is two-fold, proper compensation of harmonic current and balancing of capacitors voltage to set reference value. Instantaneous symmetrical components theory is used for generating compensating current and hysteresis control is used for current controller for shunt active power filter. Capacitors voltage drifts from set reference values due to DC component in zero sequence current. Therefore for balancing the capacitors voltage two chopper circuits independent of each other are used each for two upper capacitors and two lower capacitors, the principle being injection of equal and opposite DC mean current flowing into the respective node.

2. Five-level NPC inverter based STATCOM

2.1. Block Diagram

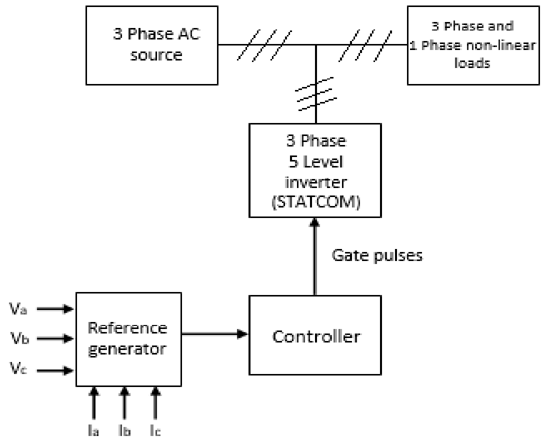


Fig. 1: Block diagram of five-level inverter based STATCOM

The Fig.1 depicts the block diagram of a three-phase system with non-linear loads and five-level inverter based STATCOM.

2.2. Circuit Description

The complete configuration of the system is shown in fig. 2. It consists of a three phase supply; loads consisting of a three phase Thyristor-bridge rectifier with RL load and two single phase semi-converters with RL load each connected to phases b and c. It also shows the five- level Diode-clamped inverter as shunt compensator injecting compensation currents into PCC. A voltage balancing circuit is shown with positive and negative bi-directional buck-boost choppers independent of each other for balancing voltages of two positive capacitors and two negative capacitors respectively. Also, the control of inverter is independent of voltage balancing circuit. It is seen from the fig. 2 the neutral of the system is tied to mid-point of four capacitors that is at node O of the five level diode clamped inverter. Here only one leg of the inverter is shown where the mid-points of diodes in each leg are connected to nodes P1, O, N1 respectively which is not shown in the figure. Consider L_f, R_f to be the filter inductor shown at ac terminals of the inverter and L_{ch}, R_{ch} be inductor for positive and negative choppers shown in the voltage balancing circuit. Let i_{cp} and i_{cn} be the positive chopper current and negative chopper current with reference polarity taken to be flowing away from nodes P1 and N1 respectively. However, the actual direction of these currents depends on the dc mean currents flowing into respective nodes.

2.3. Reference current generation

In this method, instead of using the Clarke transform to calculate instantaneous active and reactive power, it calculates directly the active and reactive parts of the load current. The currents are determined under the constraint that they must transport the same power absorbed by the load. The reactive instantaneous current in the system is a component that doesn't contribute in the active energy transfer. But, it increases the current amplitude and the losses. This current can be determined using the Lagrange method. If we suppose that the load current i_{Lk} with k=a, b, c is composed of active i_{Lka} and reactive i_{Lkb} parts as:

$$i_{LK} = i_{LKa} + i_{Lkr} \tag{3.1}$$

The principle of this method is to determine the active current in the load current with the constraint that the reactive current doesn't produce any instantaneous active power. The task is then to minimize the function L given by:

$$L(i_{La}, i_{Lb}, i_{Lc}) = {i_{La}}^2 + {i_{Lb}}^2 + {i_{Lc}}^2 \tag{3.2}$$

With the constraint that:

$$p = v_a i_{La} + v_b i_{Lb} + v_c i_{Lc} \tag{3.3}$$

The problem can be solved using Lagrange method which leads to:

$$\begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} = -\lambda \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.4}$$

In this equation, λ is given by:

$$\lambda = -\frac{2P}{v_a^2 + v_b^2 + v_c^2} \tag{3.5}$$

From Eqns. 3.4 and 3.5 the currents can be given by:

$$\begin{bmatrix} i_{Laf} \\ i_{Lbf} \\ i_{Lcf} \end{bmatrix} = \frac{\bar{P}}{v_a^2 + v_b^2 + v_c^2} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.6}$$

a) Current controller:

The five-level hysteresis can be obtained as follows.
error, e= $i_{cabc} - i^*_{cabc}$
where i_{cabc} = actual inverter current
and i^*_{cabc}= reference compensation current
'h' is the width of inner hysteresis band and δ be the width of outer hysteresis band. Then the output function is given as

$$u = \begin{cases} -2, & if\ e \geq \delta \\ -1, & if\ h \leq e < \delta \\ 0, & if - h \leq e < h \\ 1, & if - \delta < e \leq -h \\ 2, & if\ e \leq -\delta \end{cases}$$

3. DC Capacitors Voltage equalization

3.1. Voltage balancing circuit

The voltage balancing circuit consisting of two bi-directional buck-boost choppers is shown in fig. 2. For an ideal operation of compensator, no dc mean current flows into nodes P1, N1 shown in fig.2. But due to unequal charging and discharging of practical capacitances, switching losses in the inverter a small amount of dc mean current flows into nodes P1 and N1. The amount of DC current depends on the duty factor of the node and active power component of the load current which is given in [18]. The effect is that one capacitor gets over charged and the would be discharged. Therefore, if this dc mean current is countered by injecting equal and opposite averaged dc current into the respective node the capacitor voltages are restored to set values. The principle of chopper operation is that transfer of energy from over charging capacitor to discharging capacitor. If i_{P1} is mean current flowing into node P1 and $i_{cp}$is the current through positive chopper, at steady state $i_{P1}=\bar{i}_{cp}$ then
$V_{P2-P1}=V_{P1-O}$.

3.2. Controller for voltage balancing circuit

The controller for positive chopper circuit is shown in fig.3. The controller is similar for the negative chopper circuit. The voltages V_{P1-P2} and V_{P2-O} are compared and given as input to a PI controller which ensures the voltage balance at steady state. The output of PI controller is the reference current for the chopper and is compared to actual chopper current. The error is compared with a fixed frequency triangular carrier wave and the comparator provides the current control for the chopper.

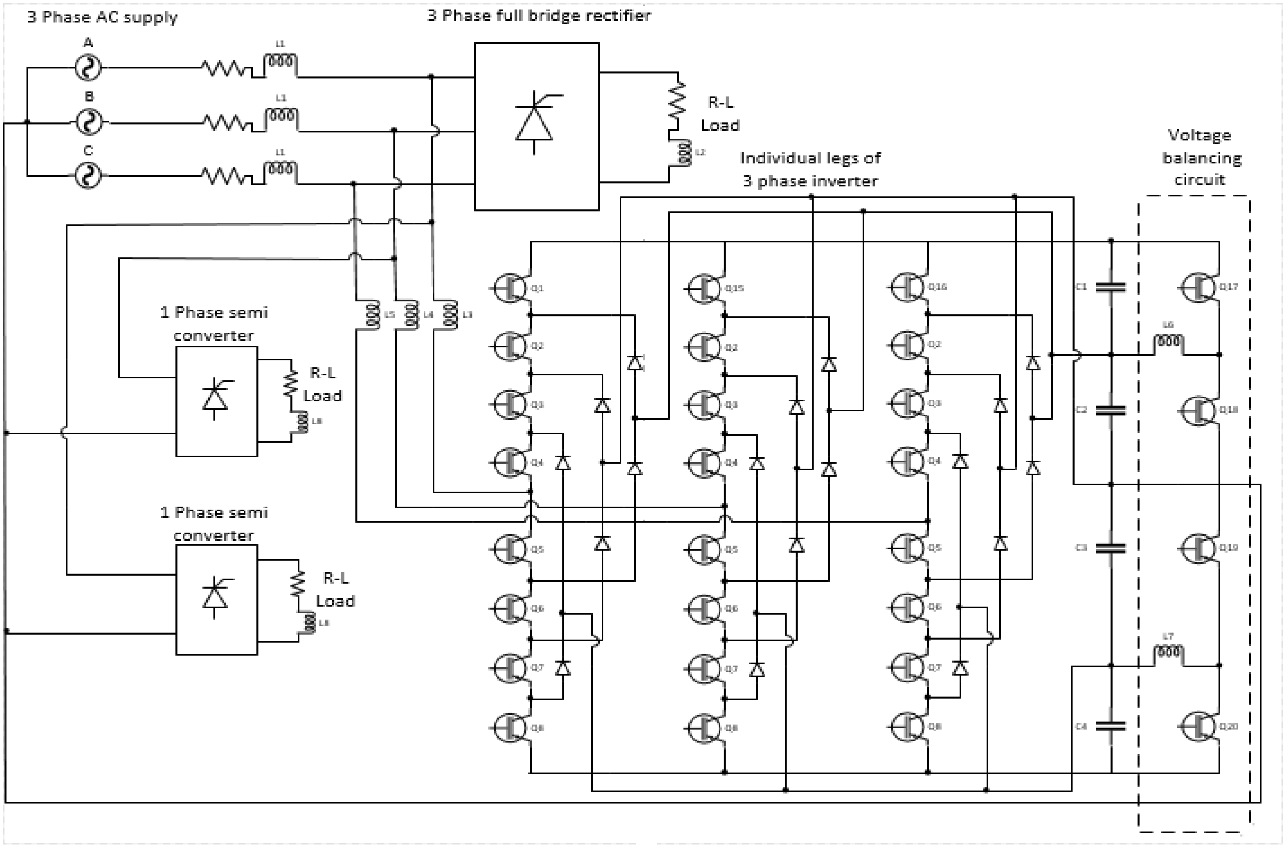


Fig. 2: Five-level NPC inverter based STATCOM and voltage balancing circuit

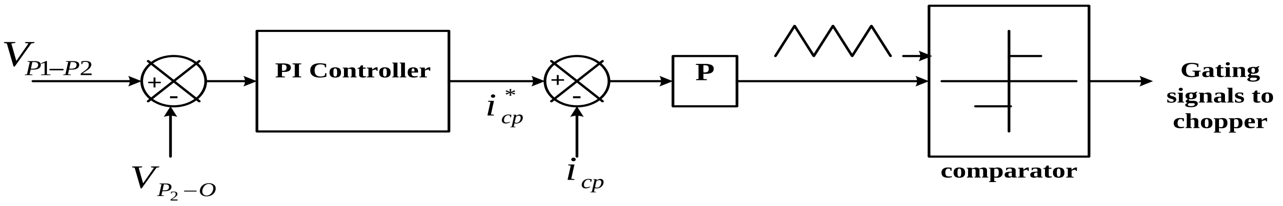


Fig. 3: Current controller for voltage balancing circuit

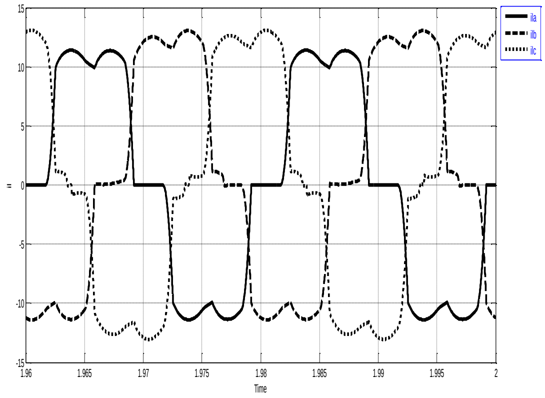
4. Simulation results

The operation of circuit for triggering fault of one of the thyristors in semi-converter in phase b cause a positive dc offset in load. The simulation results for capacitor voltage balance and harmonic current compensation is given below.

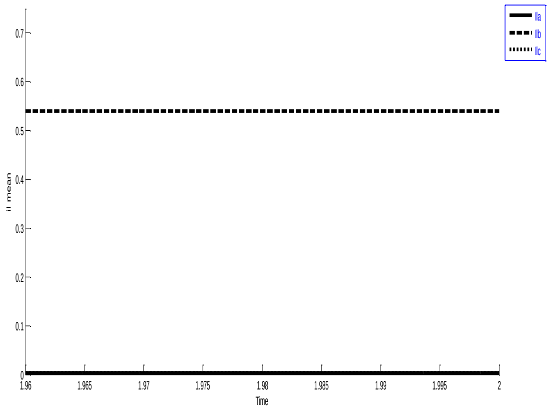
Table 1: Simulation parameters

Supply voltages	200 V (L-N peak) , 50 Hz
Three phase rectifier load	30+j6.28Ω
Single phase semi-converter loads	100+j12.56 Ω
Filter inductor (L_f, R_f)	3mH, 1m Ω
Chopper inductor (L_{ch}, R_{ch})	20mH, 1m Ω
PI controller gains	K_1= 20, I_1=100, K_2=0.1, I_2=0.1, K_3=0.1, I_3=0.1, K_4=0.1, I_4=0.1
Proportional gains for chopper current controllers	0.2
outer hysteresis band, $\pm\delta$	$\pm$0.15
Inner hysteresis band, $\pm$h	$\pm$0.05

The circuit shown in fig.2 is simulated for triggering fault of the upper thyristor in the leg connected to neutral in semi-converter in phase b. It results in rectifying only positive half cycle of the phase current b causing a positive dc offset in phase b. It flows through the neutral wire causing a dc offset in zero sequence current. These are shown in fig.4.



(a)



(b)

Fig.4: (a) Load currents. (b) DC offset in phase b.

The drift in capacitor voltage from 100V is clearly seen from fig.5. This due to the fact that the dc mean current flowing into nodes P1 and N1 is different from the values seen before due to flow of dc mean current into node O because of dc offset in phase b. It is seen from fig.6 that the voltage is asymmetrical with different amplitudes for positive and negative directions. Also the difference between successive voltage levels is not the same.

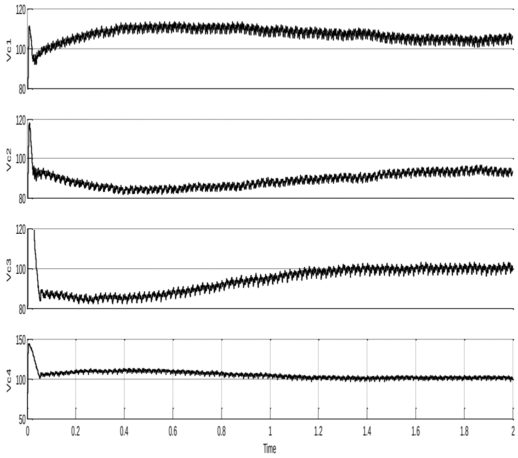


Fig.5: Capacitors voltage with DC offset in load without voltage balancing controller

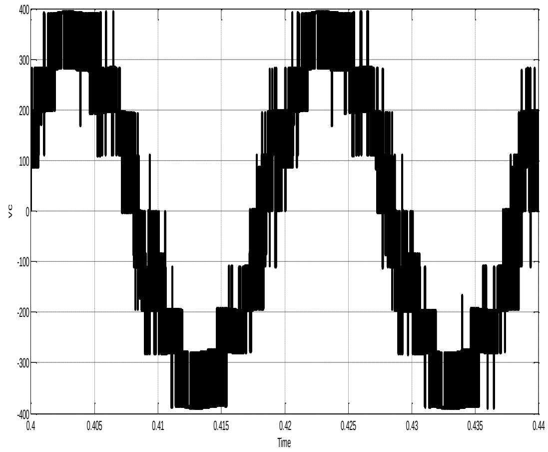


Fig.6: Line voltage at inverter ac terminals with capacitor voltage imbalance.

The capacitors voltage balance by providing voltage balancing controller with chopper circuits ON is shown in fig.7.

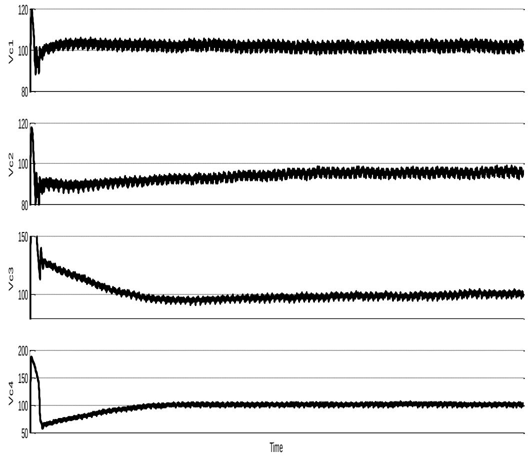
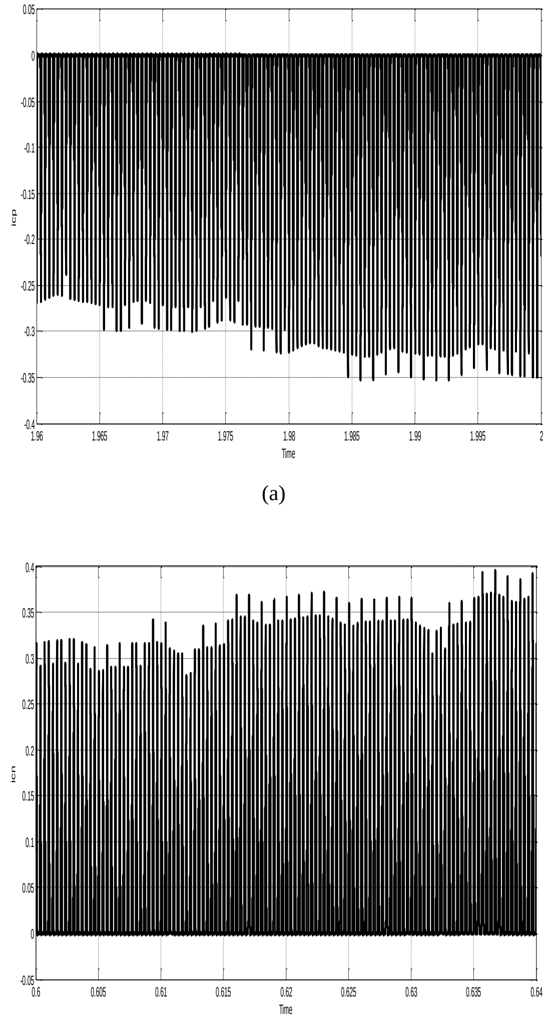


Fig.7: Capacitors voltages with voltage balancing controller and choppers ON

The positive and negative chopper currents are given in fig.8.



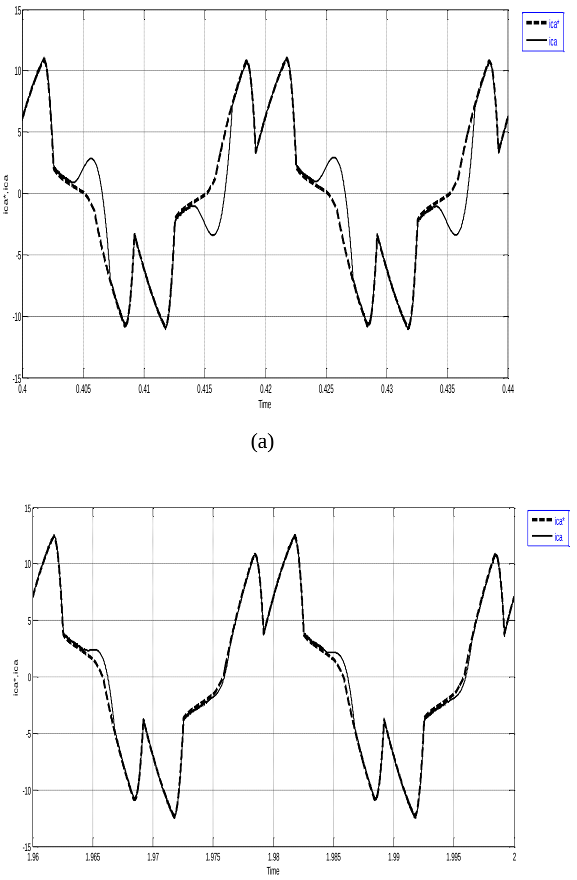
(a)

(b)

Fig.8: (a) positive Chopper current (b) negative chopper current.

Harmonic current compensation

The tracking of compensation current by the inverter is shown in Fig.9. The improvement in tracking of compensation current is observed from fig.9 where (a) gives tracking of compensation current with imbalance in capacitor voltages where only 70 percent of the reference compensation current is tracked by the inverter to that in (b) where almost 90 percent of the reference compensation current is tracked by the inverter.



(a)

(b)

Fig.9: Tracking of compensation current with
(a) capacitors voltage unbalance (b) balanced capacitors voltage

5. Conclusion

Thus, the use of a five-level diode clamped inverter for STATCOM proved advantageous making more voltage levels available helping in better tracking of compensator current. An external voltage-balancing circuit mitigates the drift in capacitors voltage caused by dc component in load. Simulation results show that the proposed controller for voltage balancing proved better restoration of tracking performance.

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