

CARRIER PWM CONTROL OF CASCADE MULTILEVEL INVERTER FOR THREE-PHASE FOUR-WIRE SHUNT ACTIVE FILTER

Nguyen Van Nho

University of Technology, HCM City

Pham Ngoc Hiep

University of Ba Ria-Vung Tau

ABSTRACT

Cascade multilevel inverters are known as perspective converters for applications. They can help to use simple integrated power modulus, simplify and avoid the problem of DC source balancing. The paper introduces a new carrier PWM technique to control the cascade inverter output. Improving electrical power quality by reducing harmonic content caused by nonlinear load will be considered. In this paper, there will be mathematically formulated and simulated for 5-level cascade inverter and applied in filtering harmonics in three-phase four-wire unbalanced load system.

I. INTRODUCTION

There are three types of multilevel inverters as NPC multilevel inverter, cascade multilevel inverter and DC capacitor clamped multilevel inverter. The NPC converters are advantageous for its simple topology. However series connected DC capacitors on DC side are continuously interacted each other and with load sides that results in a voltage unbalancing and oscillating. The performance can be drastically reduced for increasing voltage stress on switching devices and unbalance load voltages and currents. Being different from NPC inverter, cascade multilevel inverter have no problems with DC source unbalancing.

Conventional PWM technique will be considered during analysis, for which: commutation with optimal switching losses, i.e. there exist only one commutation for a transition between two subsequent switching states.

Existence of harmonics caused by different nonlinear load reduces power quality and may be a risk of non stability in normal operation. Active filter for network three-phase four-wire has been designed and controlled successfully. The method presented can be applied to three-phase four-wire active filter using 5-level cascade inverter.

In the paper, a model of cascade inverter will be presented as series connected single-leg two-level inverters and carrier modulation is

implemented using multi-modulating signals, where number of modulating signals each phase is equal to number of corresponding switching pairwise.

II. ANALYSIS OF ALGORITHM FOR CASCADE MULTILEVEL INVERTER.

1 Principle of PWM method for cascade multilevel inverter.

The carrier based PWM algorithms for cascade multilevel inverter can be deduced in a similar way as in NPC inverter and described in Fig.1. For given reference load voltage U_{ij} , the value of inverter voltage U_{j0} can be deduced, consisting of fundamental component U_{ij} and related common mode V_0 . The inverter voltage U_{j0} can be then used to produce modulating signals for individual switching pairs ξ_{jx} (For the 1st phase, it is ξ_{11} , ξ_{21} , ξ_{31} , ξ_{41}), which compare the triangle carrier wave for producing trigger signals (Fig.2-3a,b).

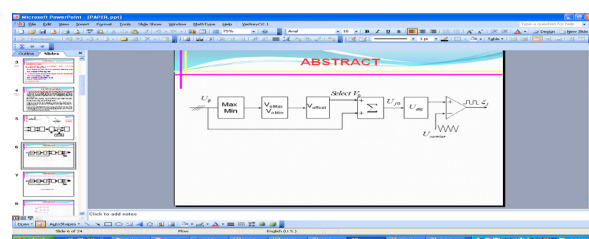


Fig.1. Principle of carrier based PWM algorithm for cascade inverter.

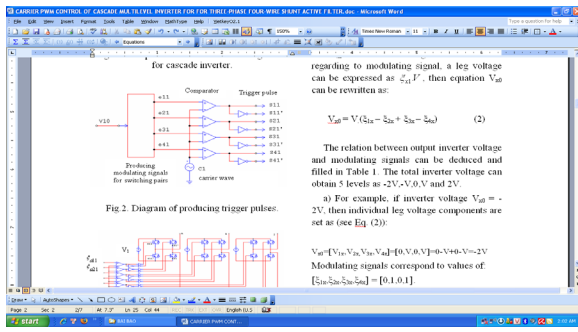


Fig.2. Diagram of producing trigger pulses.

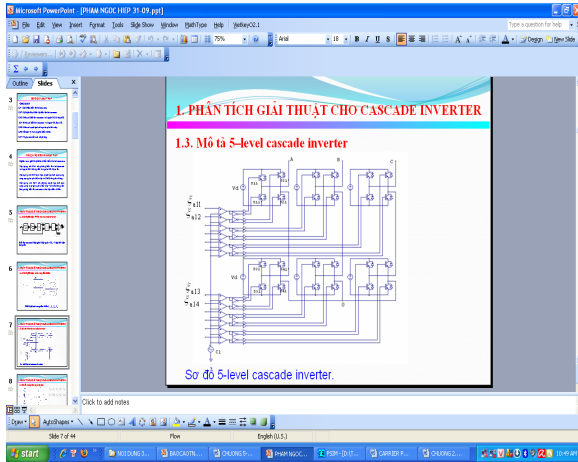


Fig.3a. Diagram of 5-level cascade inverter.

2. Analysis of PWM algorithm.

Phase inverter voltage V_{x0} can be analyzed as summation of four single leg voltage components, described by equation as:

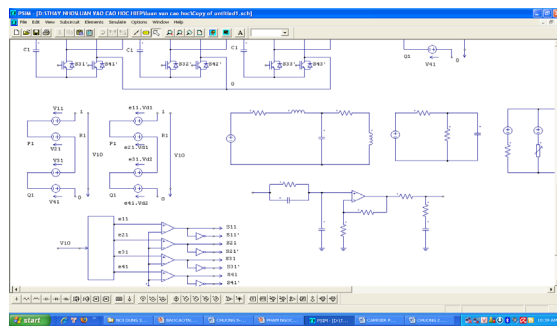


Fig.3b. Equivalent circuit of single phase

$$V_{x0} = V_{1x} - V_{2x} + V_{3x} - V_{4x} \quad (1)$$

Where V_{1x} and V_{2x} are leg voltages deduced from the 1st H-bridge inverter and V_{3x} and V_{4x} from the 2nd H-bridge inverter. Because regarding to modulating signals, a leg voltage

can be expressed as $\xi_{x1} \cdot V$, then equation V_{x0} can be rewritten as follows:

$$V_{x0} = V(\xi_{1x} - \xi_{2x} + \xi_{3x} - \xi_{4x}) \quad (2)$$

The relation between output inverter voltage and modulating signals can be deduced and filled in Table 1. The total inverter voltage can obtain 5-level as $-2V, -V, 0, V$ and $2V$.

a) For example, if inverter voltage $V_{x0} = -2V$, then individual leg voltage components are set as (see Eq. (2)):

$$V_{x0} = [V_{1x}, V_{2x}, V_{3x}, V_{4x}] = [0, V, 0, V] = 0 - V + 0 - V = -2V$$

Modulating signals correspond to values as follows:

$$[\xi_{1x}, \xi_{2x}, \xi_{3x}, \xi_{4x}] = [0, 1, 0, 1].$$

There are two inverter voltage levels as $-2V$ and $+2V$, which correspond to one switching state, other levels can be deduced from different switching state combinations. For example, voltage $V_{x0} = -V$ may be obtained equivalently from 4 switching combinations. A proper switching state can be selected in order to have periodical process to all switching pairs and meet requirement of a minimum number of switching.

b) For a given voltage V_{x0} , whose value is within two closest levels, modulating signals $\xi_{1x}, \xi_{2x}, \xi_{3x}, \xi_{4x}$ can be deduced in several steps as follows:

Step 1: to determine two voltage levels closest to V_{x0} and corresponding two leg voltage components ($V_{1x}, V_{2x}, V_{3x}, V_{4x}$).

Step 2: to determine modulating signals for individual switching pairs.

For example, it is given $-2V < V_{x0} < -V$.

Step 1: to select two leg voltage components $[0, V, 0, V]$ and $[0, V, V, V]$.

Step 2: Using Table 1, it is set $\xi_{1x} = 0, \xi_{2x} = 1; \xi_{3x} = \xi_{4x} = 1$; where $\xi_x = (V_{x0} + 2V)/V$. (Because of $V_{x0} = 0 - V + \xi_x \cdot V - V$).

In such a way, modulating signals in different voltage range for three-phase inverter can be derived.

Table 1. The reference voltage and control signal.

V_{x0}	$[V_{x11}, V_{x21}, V_{x31}, V_{x41}]$	ξ_{x11}	ξ_{x21}	ξ_{x31}	ξ_{x41}
$V_{x0} = -2V$	$[0, V, 0, V]$	0	1	0	1
$-2V < V_{x0} < -V$	$[0, V, 0, X]$	0	1	0	ξ_x
	$[0, V, X, V]$	0	1	ξ_x	1
	$[0, X, 0, V]$	0	ξ_x	0	1
	$[X, V, 0, V]$	ξ_x	1	0	1
$V_{x0} = -V$	$[0, V, 0, 0]$	0	1	0	0
	$[0, V, V, V]$	0	1	1	1
	$[0, 0, 0, V]$	0	0	0	1
	$[V, V, 0, V]$	1	1	0	1
$-V < V_{x0} < 0$	$[0, X, 0, 0]$	0	ξ_x	0	0
	$[X, V, V, V]$	ξ_x	1	1	1
	$[0, V, X, 0]$	0	1	ξ_x	0
$V_{j0} = 0$	$[0, 0, 0, 0]$	0	0	0	0
	$[V, V, 0, 0]$	1	1	0	0
	$[0, 0, V, V]$	0	0	1	1
	$[V, V, V, V]$	1	1	1	1
	$[0, V, V, 0]$	0	1	1	0
	$[V, 0, 0, V]$	1	0	0	1
$0 < V_{x0} < V$	$[X, 0, 0, 0]$	ξ_x	0	0	0
	$[0, X, V, 0]$	0	ξ_x	1	0
	$[V, V, V, X]$	1	1	1	ξ_x
	$[V, 0, 0, 0]$	1	0	0	0
$V_{x0} = V$	$[V, 0, V, V]$	1	0	1	1
	$[0, 0, V, 0]$	0	0	1	0
	$[V, V, V, 0]$	1	1	1	0
	$[V, 0, X, 0]$	1	0	ξ_x	0
$V < V_{x0} < 2V$	$[V, 0, V, X]$	1	0	1	ξ_x
	$[X, 0, V, 0]$	ξ_x	0	1	0
	$[V, X, V, 0]$	1	ξ_x	1	0
	$[V, 0, V, 0]$	1	0	1	0

Over modulation in 5-level multilevel inverter cascade: For over modulation range, the reference voltage can be produced in a similar way of conventional cascade multilevel inverter. The principle control between two limit trajectories can be used to obtain linear over modulation.

The proposed PWM method will be applied to eliminate current harmonic content in three-phase four-wire shunt active power filter, which is described in the following section.

III. SHUNT ACTIVE POWER FILTER FOR THREE-PHASE FOUR-WIRE SYSTEM

1. Shunt active power filter.

From all the power components of the p-q theory, only the mean values of the instantaneous real power (\bar{p}) and of the instantaneous zero-sequence power (\bar{p}_0) must come from the power supply, because they effectively transfer energy to the load.

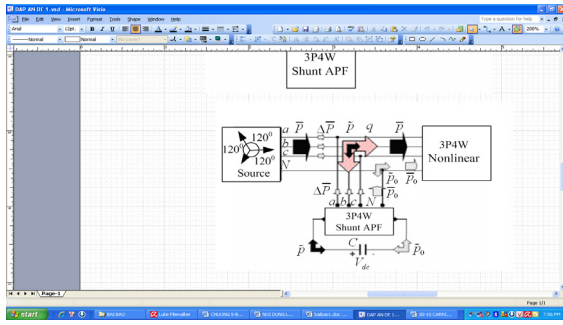


Fig.4. p-q theory power components in three-phase four-wire power system with shunt active filter.

The active filter also permits the power supply to deliver the value of \bar{p}_0 to the load from the phases, without the needing of the neutral wire. All the other power components (\tilde{p} , \tilde{p}_0 and q) can be compensated with the use of the shunt active power filter, as presented in figure 4.

The active power p and reactive power q were provided to three-phase four-wire load and expressed by formula as follows:

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} \bar{p}_L + \tilde{p}_L \\ \bar{q}_L + \tilde{q}_L \end{bmatrix} \quad (3)$$

The P_L and Q_L were provided by the active circuit filter as follows:

$$\begin{bmatrix} p_{AF} \\ q_{AF} \end{bmatrix} = \begin{bmatrix} -\bar{p}_L + \Delta\bar{p} \\ -\bar{q}_L - \tilde{q}_L \end{bmatrix} \quad (4)$$

Thus, the AC source supplies DC component of load power and the power loss of cascade inverter. Active filter provides other power components as \tilde{p} , Δp and q .

2. Analysis of active filter circuit

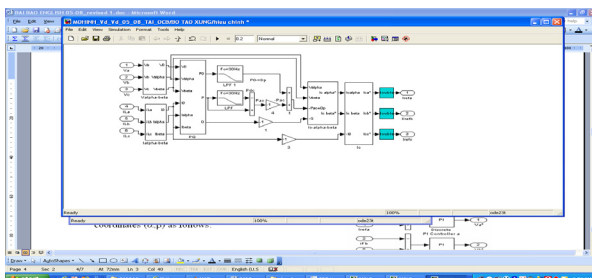


Fig.5. Diagram of producing reference current.

Let consider circuit in Fig.5. Signals i_{la} , i_{lb} , i_{lc} are load currents. Signals v_a , v_b , v_c are load voltages. Three-phase load voltages are expressed in coordinates (α, β) as follows:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (5)$$

Similar transformation for load currents:

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (6)$$

And compensating currents can be deduced from power components as follows:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{v_\alpha + v_\beta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \Delta\bar{p} \\ -\tilde{p} - \tilde{q} \end{bmatrix} \quad (7)$$

The currents are expressed in (abc) coordinates as follows:

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} -i_0 \\ i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \quad (8)$$

The required current i_{refa} , i_{refb} , i_{refc} and filter current i_{Fa} , i_{Fb} , i_{Fc} are passed PI element for producing requirement voltage V_{a^*} , V_{b^*} , V_{c^*} . The V_{a^*} , V_{b^*} , V_{c^*} were compared with carrier wave for producing trigger pulses for active filter and were shown as follows:

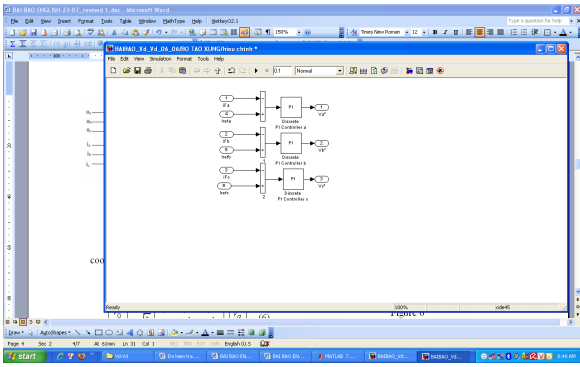


Fig.6. Diagram producing the voltage V_a^* , V_b^* , V_c^*

IV. SIMULATION RESULTS

The proposed carrier based PWM algorithm is implemented by simulation using MATLAB Simulink. The 5-level cascade inverter was built (see Fig. 7). A steady state was considered first, where diagrams of load currents, inverter voltage, load voltage and FFT analysis were shown as follows:

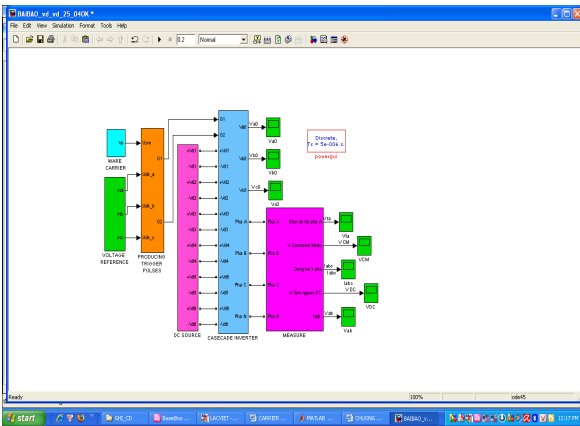


Fig.7. Model of 5-level cascade inverter using Matlab Simulink.

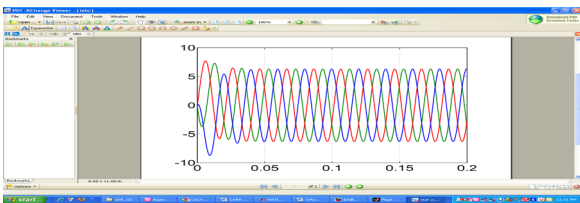


Fig.8. Diagrams of the load three-phase current

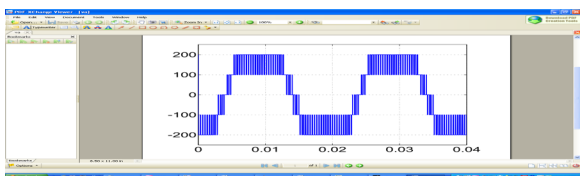


Fig.9. Diagrams of the inverter phase voltage V_{a0}

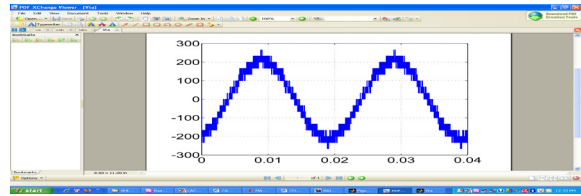


Fig.10. Diagrams of the load voltage V_{ta}

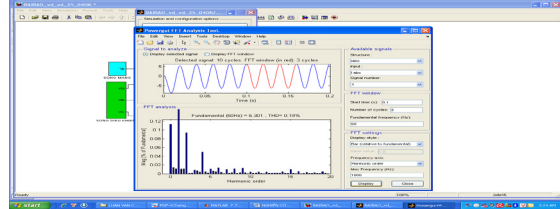


Fig.11. Results harmonic order of the load three-phase current THD is 0.19%.

In order to perform simulation the active filter three-phase four-wire network using 5-level cascade inverter. It was built in MATLAB Simulink (see Fig.12) and the parameters were set as follows:

- Three phase AC voltage: $U_f = 220V$, $f=50Hz$.
- Three phase controlled rectifier as unbalanced load, its output DC voltage is set equal to $U_{DC} = 250V$; $R = 2.4\Omega$; $L = 6e-3H$.
- Single phase rectifier to perform unbalanced load with $R = 30\Omega$; $L = 5e-3H$.
- The carrier frequency is set as $f_c = 3kHz$.

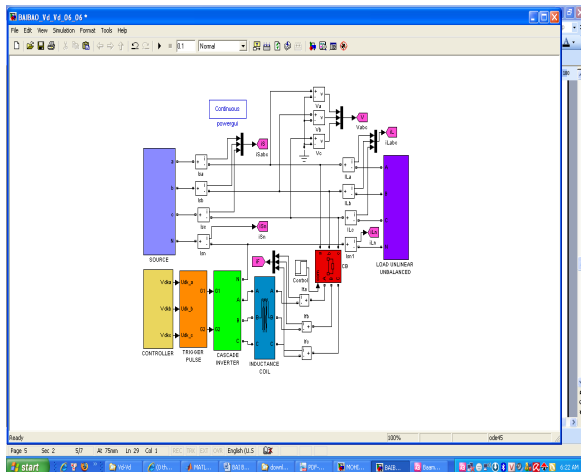


Fig.12. Model of active filter using 5-level cascade inverter.

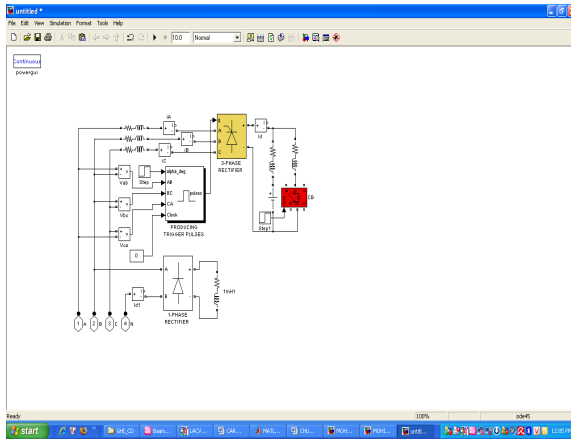


Fig.13. Model of unbalanced three-phase four-wire load.

The simulation results:

The case study 1: Unbalanced three-phase four-wire constant load.

Active power filter is applied at 0,1s. The simulation results:

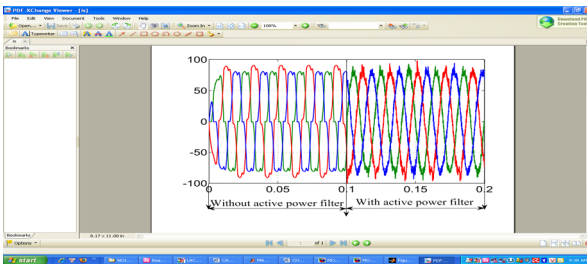


Fig.14. Diagrams of source three-phase current.



Fig.15. Diagrams of source effective three-phase current.

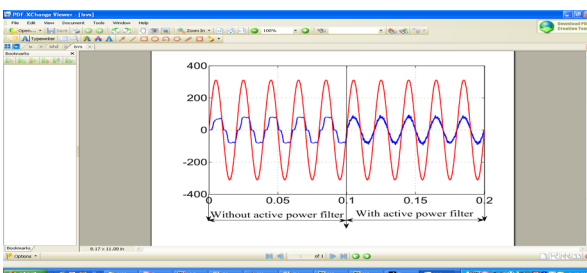


Fig.16. Diagrams of the source current and source voltage are in-phase

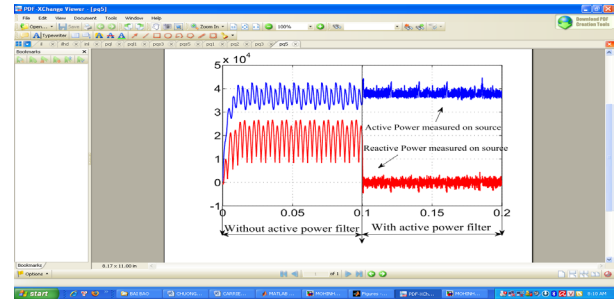


Fig.17. Diagrams of active power and reactive power.

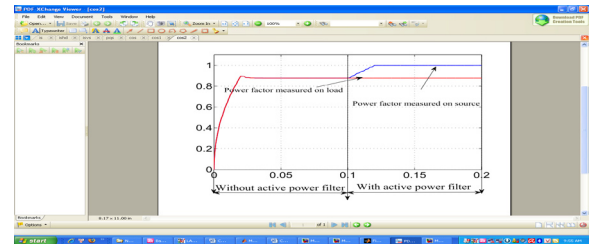


Fig.18. Diagrams of power factor measured on load and AC source.

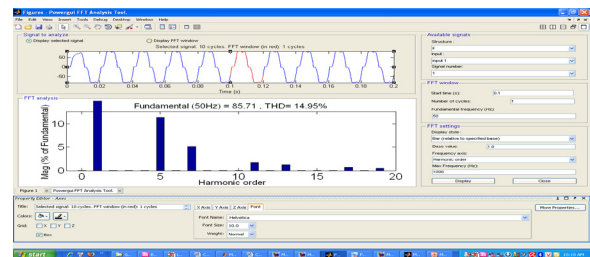


Fig.19. Results harmonic order of source current without filter THD is 14.95%.

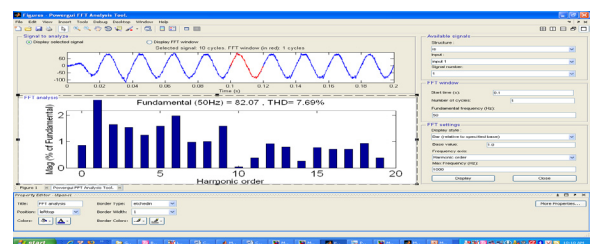


Fig.20. Results harmonic order of source current with filter THD is 7.69%.

The case study 2: Unbalanced three-phase four-wire change load.

At starting point, active filter is applied. The unbalanced three-phase four-wire load was changed at the time of 0,1s. Phase angle of three-phase rectifier was changed from 0 to 90 degrees at the time of 0,2s. The simulation results:

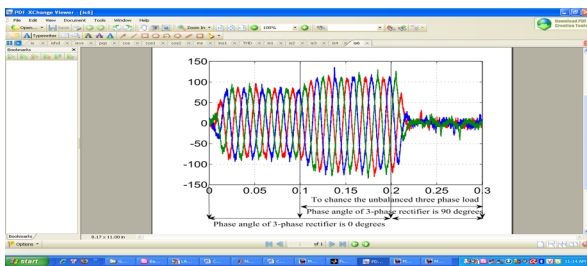


Fig.21. Diagrams of source three-phase current.

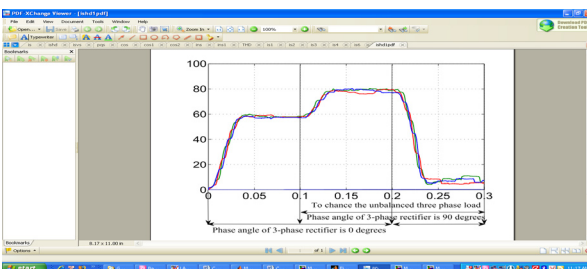


Fig.22. Diagrams of source effective three-phase current

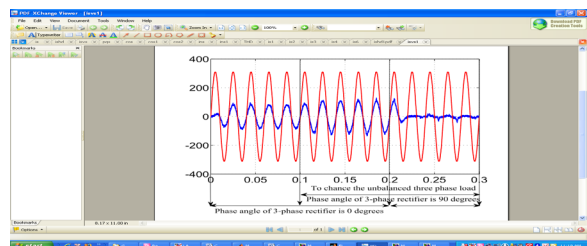


Fig.23. Diagrams of the source current and source voltage are in-phase

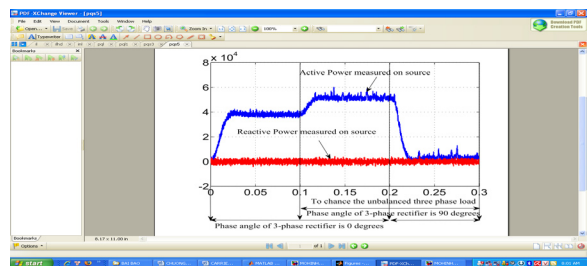


Fig.24. Diagrams of active power and reactive power.

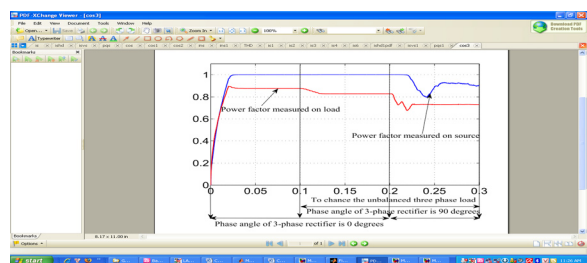


Fig.25. Diagrams of power factor measured on load and AC source.

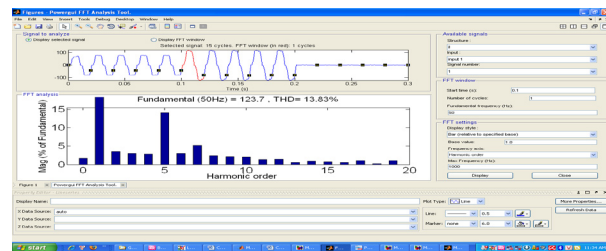


Fig.26. Results harmonic order of source current without filter THD is 13.83%.

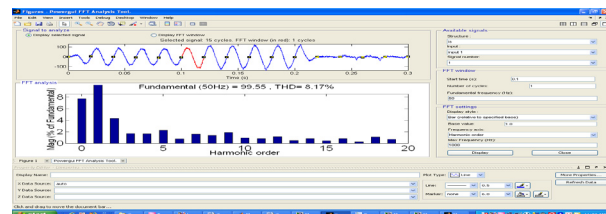


Fig.27. Results harmonic order of source current with filter THD is 8.17%.

V. CONCLUSION

The paper has proposed a new carrier based algorithm PWM for 5-level cascade inverter. The described PWM algorithm has been evaluated using simulation. As a possible application, the cascade multilevel inverter scheme and proposed PWM algorithm has been used to three-phase four-wire active power filter. From the simulation results, the active filter response has eliminated nearly the impact of load unbalance. It cleans and balances the source three-phase current.

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