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THREE-PHASE THREE-LEVEL VOLTAGE SOURCE INVERTER WITH VOLTAGE BALANCER - A SIMULATION STUDY IN MATLAB/SIMULINK

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ABSTRACT

A model of three phase three level voltage source inverter (VSI) with voltage balancer circuit employing hysteresis current control is developed in MATLAB/SIMULINK. With this proposed model, design and analysis of the inverter becomes simplified avoiding convergence problem and considerable reduction in simulation run time is achieved. The voltage and current ratings of power semiconductor switches and load current can also be determined. The simulation study shows that voltage balancer circuit maintains average voltages across two d. c. link capacitors constant and equal. Harmonic analysis of inverter output voltage and load current shows that total harmonic distortion is 9.14% and 1.77% respectively.

Key words: Multilevel inverter, switching function, harmonics, voltage balancer.

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1. INTRODUCTION

The introduction of multilevel inverters in 1990s has revolutionized power electronics industry. A multilevel inverter (MLI) generates a sinusoidal voltage from several levels of d. c. voltages which are obtained from capacitor voltage sources [1-5]. However, a major disadvantage in MLI is imbalance in the capacitor voltages which creates distortions in output voltages of inverter. The other disadvantages are higher number of power switches, increase in switching losses and complex control circuitry. There are three types of MLIs which have become popular [1]. These are neutral point clamped (NPC), flying capacitor MLI and cascaded MLI which are employed in STATCOM circuits [6-12]. Of these MLIs, neutral point clamped (NPC) multilevel inverter has found many applications in industry.

The advantages of using NPC multilevel VSI can be stated briefly as follows:

- As the number of levels increases, harmonic content of output voltage decreases at the same switching frequency.
- Selective harmonic elimination can be employed to effect further reduction of harmonics.
- Zig-zig connection of transformers needed in conventional multi-pulse converters are avoided.
- Efficiency of power conversion improves.
- Active and reactive power flows can be controlled independently with ease.

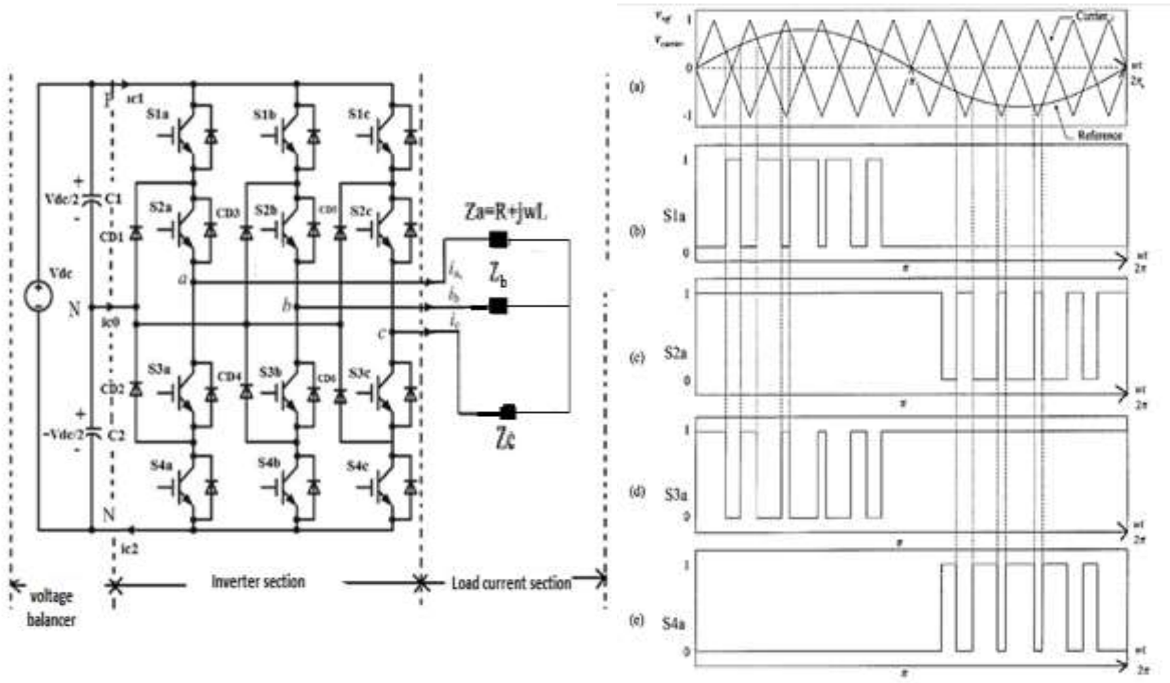
Therefore, this paper has taken up the simulation study of NPC multilevel inverter. A simulation study carried out in MATLAB/ SIMULINK has many advantages. These are: steady state and transient performance of the circuit can be predicted without fabrication of actual hardware and improvements in the circuit performance can be done by modifications in circuit configuration at no cost. Rather simulation is a first step; and then ratings of all circuit components can be decided after effecting improvements. Thereafter one can proceed to construct the hardware.

In MATLAB, proper state equations are needed to describe the power conversion circuit. Obtaining the state equations for complex circuit are difficult and time-consuming job because number of variables increase with complexity of circuits. New state equations have to be re-written afresh for every minor change in the circuit configuration. Therefore, the concept of switching function is introduced to simplify this task [2].

This paper is organized in the following manner. The second section of this paper describes working of three-phase three-level voltage source inverter in brief. The development of switching function concept to generate gate pulses is discussed in section III. The SIMULINK model of three phase three level VSI is developed in section IV. Simulation methodology and results are presented in section V. The paper concludes with section VI.

2. WORKING OF THREE PHASE THREE LEVEL VSI

Fig.1(a) shows power circuit diagram of a three phase three level IGBT based voltage source inverter (VSI) supplying a balanced three phase inductive load. There are four switches in each phase. The inner devices of phase ‘a’ viz. S_{a2} and S_{a3} conduct for 180 deg. and outer devices S_{a1} and S_{a4} conduct for less than 180 deg. The gate signals for phase ‘a’ are generated by comparing triangular wave of 1kHz frequency with a sine wave of 50 Hz frequency. This is known as sinusoidal pulse width modulation (SPWM). Same is the case for the devices of phase ‘b’ and phase ‘c’. The gate signals for devices in phase ’b’ and phase ’c’ are respectively displaced by phase shift of 120deg. and 240deg. with respect to control signals of phase ‘a’. The output voltage of inverter is a stepped waveform. The function of diodes connected across switching devices is to clamp the voltage for the duration for which outer devices are not conducting. Two charged d. c. capacitors with the midpoint as neutral act as d. c. source to the inverter. A provision is made to charge the capacitors through a rectifier connected to an a. c. source. Practice has shown that imbalance is also present in the two capacitor voltages leading to distorted waveforms of output voltage and current. Hence it is necessary to balance voltages across capacitors and also to maintain d. c. link voltage constant. This is achieved by a voltage balancer circuit.



(a) (b)

Figure 1. (a) Power Circuit diagram of three phase three level VSI (b) (i)Reference and carrier waveforms (ii) Switching function for switch S1a (iii) Switching function for switch S2a (iv) Switching function for switch S3a (v) Switching function for switch S4a

3. SWITCHING FUNCTION AND ITS USE

For a voltage source inverter, the output voltage Vo can be related to input voltage Vi by

$$Vo(wt) = S(wt).Vi(wt) \quad (1)$$

where, S(wt) is defined as switching function of the inverter [2-4].

Switching function depends on type of inverter and gating pattern of the switches. Using the switching function, the detailed relationship between the input and output variables can be obtained. Therefore, obtaining the proper switching function is very important in order to describe the role of inverter.

Neglecting the losses in the inverter switches and using power balance,

$$Vi(wt)\ Ii(wt) = Vo(wt)\ Io(wt) \quad (2)$$

$$S = Vo(wt)/Vi(wt) = Ii(wt)/\ Io(wt) \quad (3)$$

4. MODELLING OF THREE PHASE THREE LEVEL VSI

Using switching function concept, a functional model for the VSI is developed in MATLAB/Simulink. It consists of five sections: switching function section, three-phase three-level inverter section, load section and voltage balancer section as indicated by dotted lines in Fig.1(a).

4.1. SIMULINK model for Switching Functions

A triangular carrier wave of frequency 1 kHz is compared with a sine wave of 50 Hz and switching function based on sinusoidal PWM (SPWM) is obtained. In a three phase three level NPC inverter, two carriers are needed with a phase shift of 180 deg. between them because four switching functions need to be generated. The comparison of first carrier wave with reference sine wave gives control signals for S_{1a} and S_{3a}. The comparison of second carrier with reference sine wave gives control signals for S_{2a} and S_{4a}. This is shown in Fig.1(b). The control signal for switch S_{1a} is complimentary with S_{3a}. Similarly, S_{2a} is complimentary with S_{4a}. Switching function for b and c phases are obtained similarly by giving a phase shift of $120°$ and $240°$ respectively to the reference sine wave.

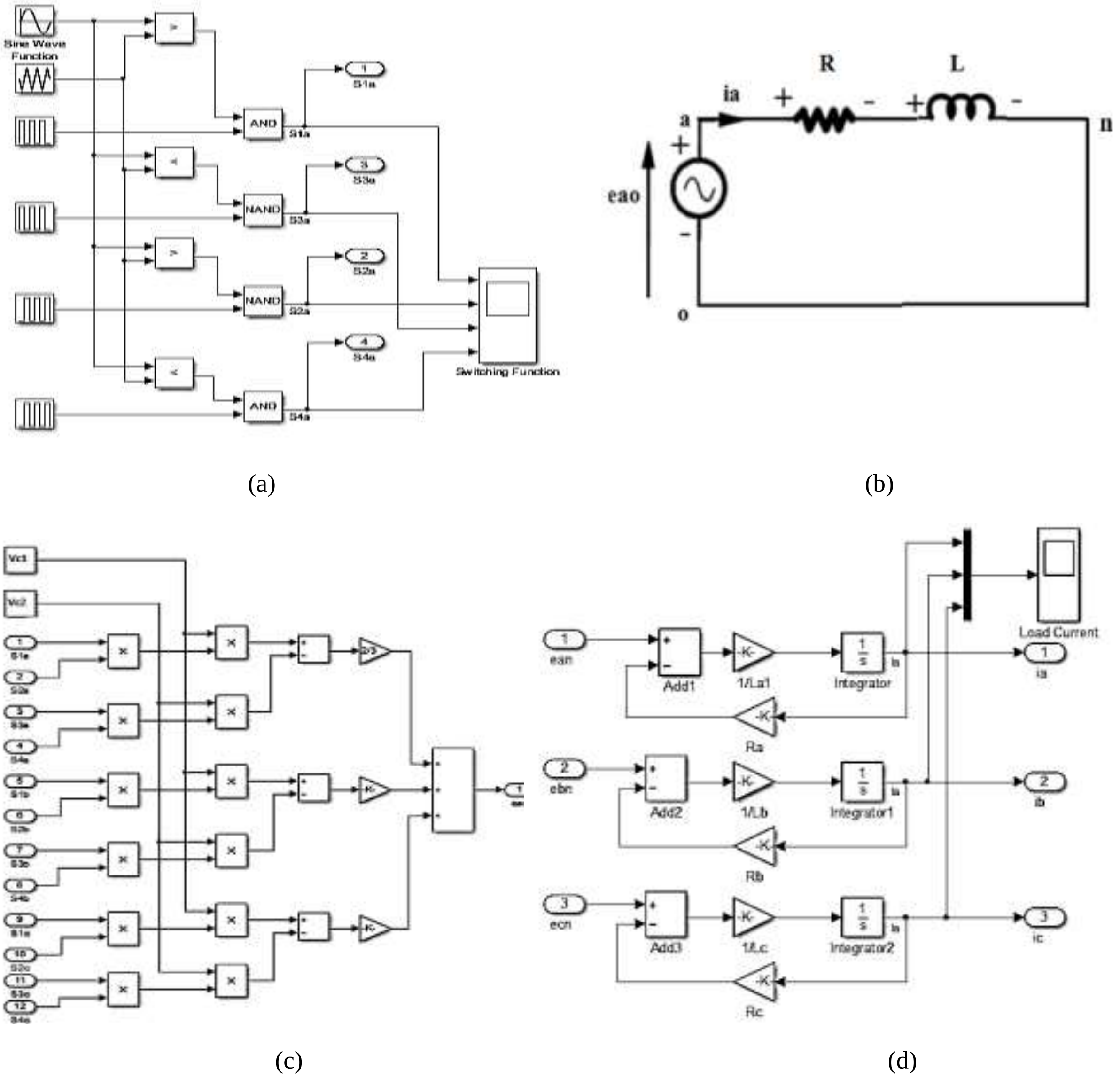


Figure 2(a). Simulink model for Switching function for phase' a' (b) Per phase equivalent circuit diagram of inverter (c) Simulink model for the determination of Phase voltage e_{ao} (d) SIMULINK model of load current

4.2. SIMULINK Model of Inverter

Equivalent circuit per phase of inverter is shown in Fig.2(b). R and L represent per phase values of load.

The voltages e_{an}, e_{bn}, e_{cn} can be obtained as

$$e_{an} = e_{ao} - e_{no}$$
$$e_{bn} = e_{bo} - e_{no} \qquad (4)$$

$$e_{cn} = e_{co} - e_{no}$$

For balanced set of these voltages

$$e_{an} + e_{bn} + e_{cn} = 0 \quad (5)$$

Therefore, from equation (4), the voltage e_{no} can be obtained as

$$e_{no} = \frac{1}{3}(e_{ao} + e_{bo} + e_{co}) \quad (6)$$

It is observed during experiment that "o" and "n" nodes [Ref fig.2(b)] are almost at zero potential with reference to ground, and therefore e_{no} is negligible

Hence,

$$e_{ao} \cong e_{an}$$
$$e_{bo} \cong e_{bn} \quad (7)$$
$$e_{co} \cong e_{cn}$$

The Simulink model for voltage e_{ao} is obtained as shown in Fig.2 (c). Similarly, SIMULINK models for e_{bo} and e_{co} are developed.

4.3. Simulink Model for Load Current

Referring to Fig.4 the equation for e_{ao} can be written as

$$e_{ao} = i_a R_a + L\frac{d_{ia}}{dt} \quad (8)$$

Equation (8) can be rearranged as shown in equation (9)

$$\frac{di_a}{dt} = -\left[\frac{R_a}{L}\right].i_a + \frac{1}{L}[e_{ao}] \quad (9)$$

Similarly, expressions for $\frac{di_b}{dt}$ and $\frac{di_c}{dt}$ can be obtained as

$$\frac{di_b}{dt} = -\left[\frac{R_b}{L}\right].i_b + \frac{1}{L}[e_{bo}] \quad (10)$$

$$\frac{di_c}{dt} = -\left[\frac{R_c}{L}\right].i_c + \frac{1}{L}[e_{co}] \quad (11)$$

In matrix form these equations (9), (10) and (11) are written as

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{R}{L} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L}\begin{bmatrix} e_{ao} \\ e_{bo} \\ e_{co} \end{bmatrix} \quad (12)$$

Simulink model for load current is developed by using (12) after replacing e_{ao} by e_{an}, e_{bo} by e_{bn} and e_{co} by e_{cn}. Simulink model of load current block is shown in Fig 2(d).

4.4. Voltage Balancer Circuit

The circuit configuration of the voltage balancer circuit is shown in Fig.3. The main function of this circuit is to maintain voltages across two capacitors equal and constant thereby maintaining the dc-link voltage (Vdc) to a desired constant value. The voltage balancer circuit is shown in Fig.3. The conventional output voltage feedback control is not employed in the voltage balancer circuit. In the conventional control the duty cycle of switch is kept constant and the input current is is found to have a large fifth harmonic component and this degrades the performance of control and increases the cost. To solve this problem, hysteresis current control is used to improve the input power factor and reduce harmonic levels. The important function is to make the ac input current (i_s) nearly in phase with source (v_s) because of which input power factor is maintained near unity.

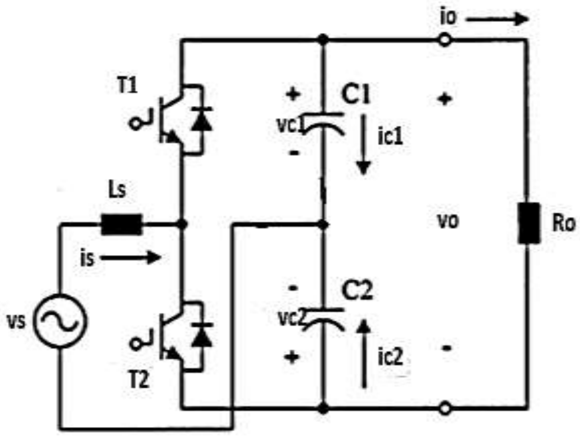


Figure 3 Voltage balancer circuit

In hysteresis control, switching boundaries are defined in terms of a single state variable viz. current (is) in this case. A dead band should also be provided to avoid chattering of switches [5]. Two boundaries with a small separation control the switching on action of the switches. Consequently, the switching action of the switches T1 and T2 is controlled by restricting value of current (is) between lower and upper limits (L1 and L2) L1<L2.

The Hysteresis current control can therefore be detailed as stated below---

Duration t1: Is ≥ Upper Limit (L2) --- T1 is turned on

Duration t2: Is ≤ Lower limit (L1) ---- T2 is tuned on

Duration t3: L1 ≤ Is ≤ L2, dis/dt >0---T2 is turned on

Duration t4: L1≤ Is ≤ L2, dis/dt <0 ---T1 is turned on

As a result, the output of the current controller will be the switching function signal for T1 and T2. When this signal is +1, it indicates conduction state of T1 and when it is -1 it indicates conduction state of T2.

Voltage and current equations can therefore be written as given in (13) to (20)--

$$\frac{dis}{dt} = 1/Ls(Vs - Vc1), \text{ T1 is turned on} \quad (13)$$
$$\frac{dis}{dt} = 1/Ls(Vs - Vc2), \text{ T2 is turned on} \quad (14)$$
$$ic1 = is - io, \text{ T1 is turned on} \quad (15)$$
$$ic1 = -io, \text{ T2 is turned on} \quad (16)$$
$$ic2 = io, \text{ T1 is turned on} \quad (17)$$
$$ic2 = is + io, \text{ T2 is turned on} \quad (18)$$
$$is = \frac{C1dvc1}{dt} + Vo/Ro, \text{ T1 is turned on} \quad (19)$$
$$is = \frac{C2dvc2}{dt} - Vo/Ro, \text{ T2 is turned on} \quad (20)$$

Based on (13) to (20), Simulink model of voltage balancer circuit is built and is shown in Fig. 4.

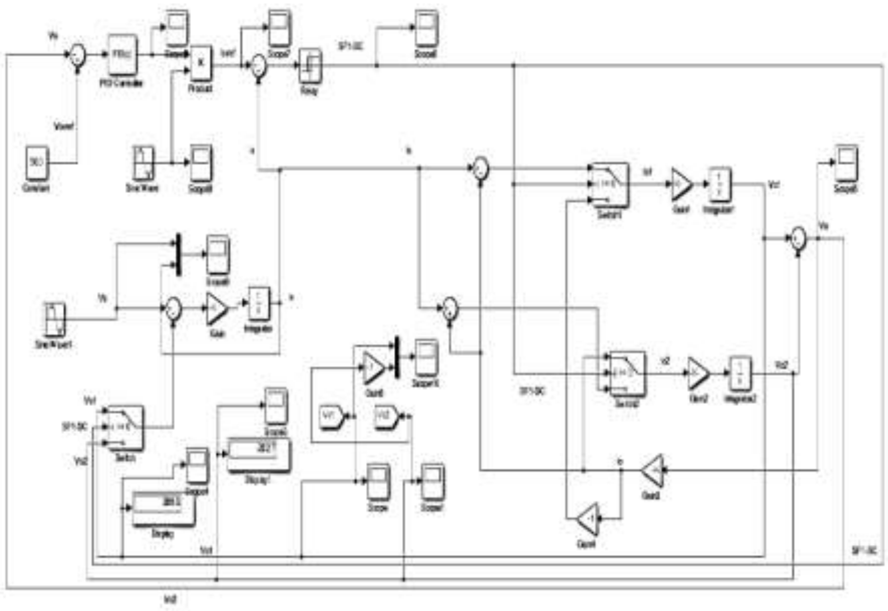


Figure 4 Simulink Model of Voltage Balancer Circuit

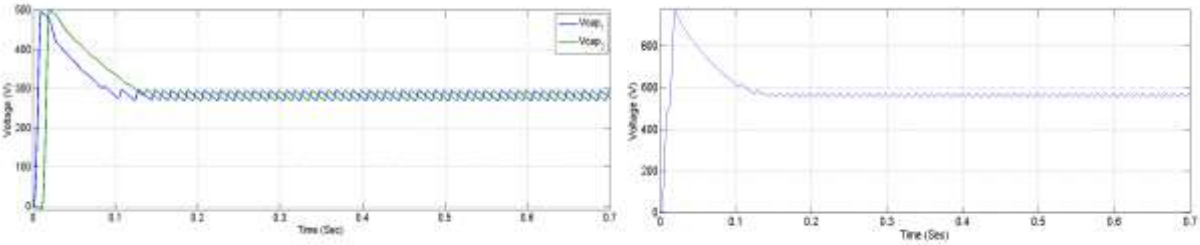
5. SIMULATION METHODOLOGY AND RESULTS

It is implemented in MATLAB/SIMULINK. The circuit parameters used in simulation and other details are given in Table I.

Table 1 Circuit parameters and simulation details

Sr. No.	PARAMETER	VALUE
1.	A.C. Input voltage, Vs	230 V (R.M.S.)
2.	Load Resistance/phase, R	2.64 ohm
3.	Load inductance/phase, L	79 mh
4.	Type of solver	ode23tb
5.	Simulation time	2 sec.

The overall SIMULINK model of three phase three level VSI with voltage balancer circuit consists of all the sections described above. Simulation is carried out and waveforms of different variables are observed as shown in Fig. 5 to Fig. 8.



(a) (b)

Figure 5 (a) Voltages across two capacitors (b) D. C. Link voltage

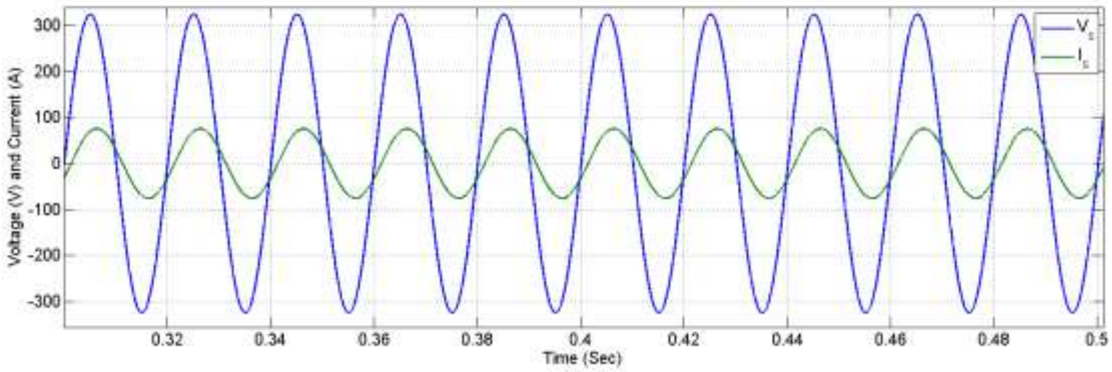
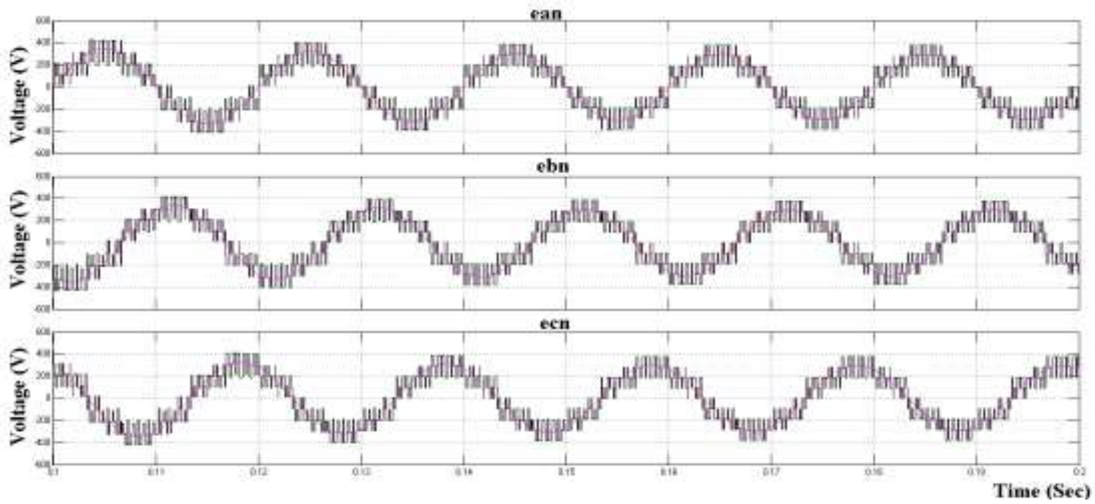
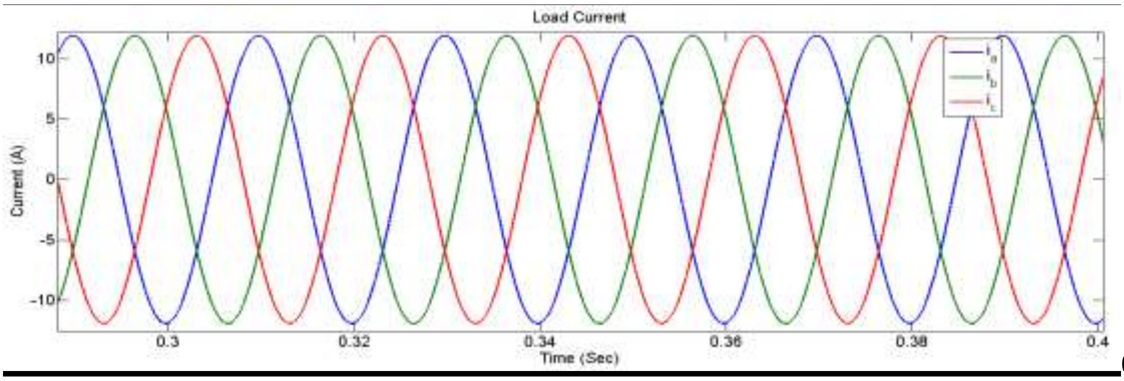


Figure 6 Source voltage and source current (fundamental)

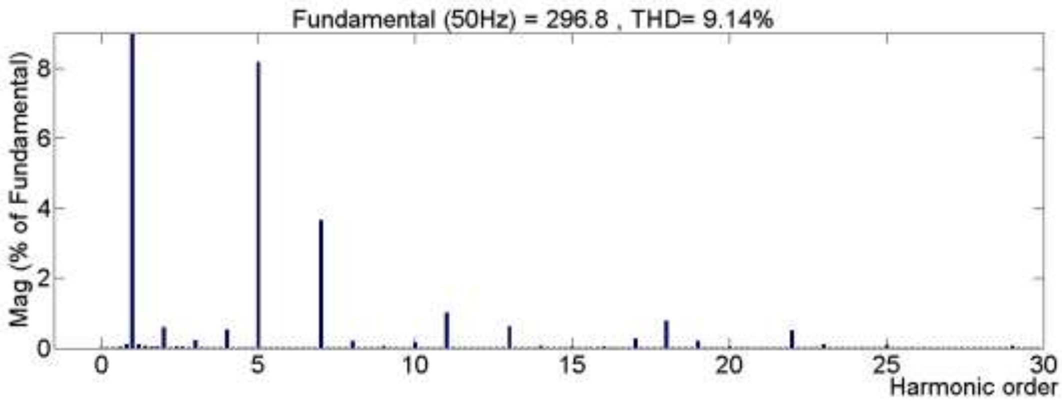


(a)

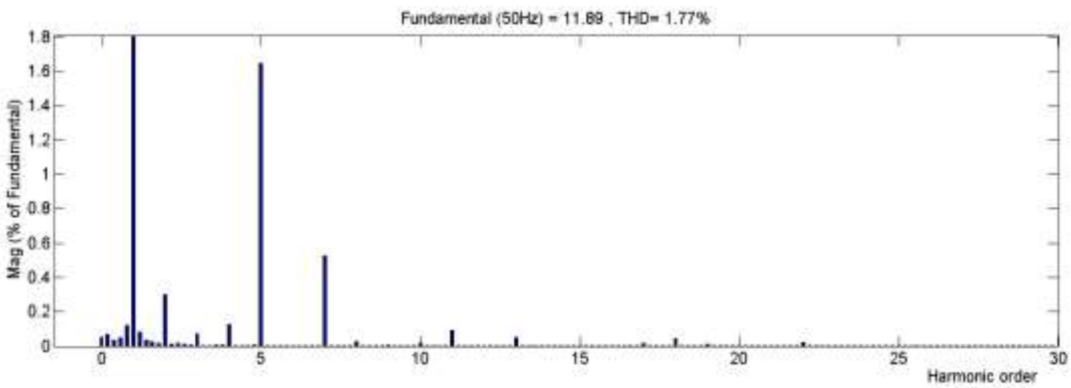


(b)

Figure 7 (a) Phase voltages across load with fundamental waveform superposed (b) Load currents



(a)



(b)

Figure 8 (a) Harmonic analysis of phase voltage (b) Harmonic analysis of load current

Voltages across two capacitors are shown in Fig.5(a). They are found to be almost equal, as desired. The D.C. link voltage is shown in Fig.5(b). It is observed that it remains almost constant. The source voltage and source current shown in Fig.6. are found to be almost in phase. (Is) is found to be almost sinusoidal. Phase voltages across load are shown in Fig.7(a). Three-phase load currents are shown in Fig.7(b). Harmonic analysis of phase voltage and load current is carried out and result is shown in Fig.8(a) and 8(b). It is observed that THDs of phase voltage and load current are respectively 9.14% and 1.77%. Introduction of filter at the output terminals of the inverter can further reduce the harmonic levels. The validation results cannot be included at this juncture as the fabrication of hardware is incomplete.

6. CONCLUSIONS

A model of three phase three level VSI with voltage balancer circuit employing hysteresis current control is developed in MATLAB/SIMULINK. Results show that voltage balancer circuit maintains voltages across two capacitors equal so that d. c. link voltage remains constant. The proposed model can be effectively utilized in design and analysis of power conversion system with different PWM control techniques. Any control strategy can be easily examined for implementation with the help of developed Simulink model.

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