

Design and Simulation of Single-Phase Multilevel Inverter fed Asynchronous Motor Drive with Less Number of Circuit Components Topology.

G. C. Diyoke¹, O. A. Ekwe²

Michael Okpewara University Of Agriculture, Umudike Umuahia, Abia State, Nigeria^{1&2}

ABSTRACT-This paper deals with study of single-phase three-level and four-level inverter fed asynchronous motor drive. Both three-level and four-level inverters are realized by an improved inverter topology with less number of circuit components. The poor quality of voltage and current of a conventional inverter fed asynchronous motor is due to presence of harmonic contents and hence there is significant level of energy losses. The multilevel inverter is used to reduce the harmonic contents but calls for high number of circuit counts. The inverter with a large number of steps can generate a high quality voltage waveform. The higher inverter levels can be modulated by comparing a rectified sinusoidal reference signal and multiple triangular carrier signals by the means of pulse width modulation technique. The simulation of single-phase three-level and four-level inverter fed asynchronous motor model is done using MATLAB/SIMULINK^R (The Math Works, Natick, Massachusetts, USA). The Fast Fourier Transform (FFT) spectrums of the outputs are analyzed to study the reduction in the harmonic contents.

Key Words: Asynchronous Motor, Matlab/Simulink, Multilevel inverters, Pulse width modulation, Total harmonic distortion.

1 INTRODUCTION

Adjustable speed drives are the vital and endless demand of the industries and researchers. Asynchronous motors are widely used in the factories and industries to control the speed of

• *Gerald Chidozie Diyoke is currently pursuing Ph.D degree program admission in Power Electronics device in University of Nigeria, Nsukka, Mob-+2348032886906. E_mail:geraldiyoke@gmail.com*

• *Ogbonna A. Ekwe obtained his bachelor of Engineering degree in University of Nigeria, Nsukka, and master's degree in Electronic and computer Engineering from University of Nottingham, United Kingdom. Mob-+2348109678739. E_mail:ogbonnaekwe@gmail.com.*

conveyor systems, blower speeds, machine tool speeds and applications that require adjustable speed controls.

Thus, single-phase asynchronous motors are extensively used for smaller loads, such as household appliances like fans, blowers, centrifugal pumps, washing machine grinder, water

pumps, etc. These motors are available in the size ranging from 1 / 20 to 1 / 2 KW. In many industrial

applications, traditionally, DC motors, provide excellent speed control for acceleration and deceleration with effective and simple torque control. The supply of a DC motor connects directly to the field of the motor allows for precise voltage control, which is necessary with speed and torque control applications. DC motors perform better than AC motors on the some traction equipment. They are also used for mobile equipment like golf cart, quarry and mining equipment. DC motors are conveniently portable and well suited to special applications, such as industrial tools and machinery that is not easily run from remote sources. But, they have inherent demerit of commutator and mechanical brushes, which undergo wear and tear with the passage of time. In most cases, AC motors are preferred to DC motors, in particular, an asynchronous motor due to its simple design, low cost, reliable operation, easily found replacements or low maintenance, variety of mounting styles, many environmental enclosures, lower weight, higher efficiency, improved ruggedness. All these and more features make the use of induction motor compulsory in many areas of industrial applications. The main demerit of AC motor, when compared with

DC motor, is that its speed is more difficult to control. AC motors can be equipped with variable frequency/PWM drives, which provide smooth turning moment, or torque, at low speeds and complete control over the speed of the motor up to its rated value. Variable frequency drive improves speed control, but do create losses with reduced power quality [1].

The advancement in Power Electronics and semiconductor technology has triggered the development of high power and high speed semiconductor devices in order to achieve a smooth, continuous and step less variation in motor speed. Applications of solid state converters/inverters for adjustable speed induction motor drive are wide spread in electromechanical systems for a large spectrum of industrial systems, “[2], [3], [4]”. As far as convectional two-level inverter is concerned, it exhibits many problems when used in high power application “[5], [6]”. Poor quality of output current and voltage of an asynchronous motor fed by a classical/ convectional two-level inverter configuration is due to the presence of harmonic content. The presence of significant amount of harmonic makes the motor to suffer from severe torque pulsations, especially at low speed, which manifest themselves in cogging of the shaft. It will also causes undesired motor heating and Electromagnetic interference [7]. Minimization in harmonics calls for large sized filter, resulting increased size and the cost of the system. The advancements in the field of power electronics and microelectronics made it possible to reduce the magnitude of harmonics with multilevel inverters, in which the number of levels of the inverters are increased rather than increasing the size of the filters [8]. Nowadays, multilevel inverters have been gained more attention for high power application in recent years which operate at high switching frequencies while producing lower order harmonic components. Multilevel inverter not only achieves high power ratings, but also enables the use of renewable energy sources [9].

In this paper Single-phase three-level and four-level inverter fed asynchronous motor drive are designed and simulated. Both the different levels are realized by using improved multilevel inverter topology. The simulations are done using

Matlab/Simulink/SimPowerSystems software with PWM control. The FFT spectrum for the output voltages and currents are analyzed to study the reduction in the harmonic contents.

2. MULTILEVEL INVERTER

Multilevel inverters have drawn tremendous interest in the power industry applications. They present a new set of features that are well suited for use in reactive power compensation. Multilevel inverters will most importantly reduce the magnitude of harmonics and increases the output voltage and power without the use of step-up transformer.

Numerous multilevel inverters topologies have been proposed during the last decades. Modern research, have involved novel inverter topologies and unique modulation techniques [10]. Basically, three different major multilevel inverter topologies have been reported in the literature, which includes: diode clamped (neutral clamped) inverter, flying capacitors (capacitor clamped) inverter, and cascaded H-bridge. Multilevel inverter presented in this paper consists of improved inverter configuration connected to split-phase single-phase asynchronous motor. The general function of this multilevel inverter is to synthesize a desired voltage from several DC sources.

3 PROPOSED SINGLE-PHASE THREE-LEVEL AND FOUR-LEVEL INVERTER CIRCUIT CONFIGURATIONS USING IMPROVED TOPOLOGY.

The proposed single-phase three-level and four-level were developed from the convectional H-bridge voltage source inverter topology. Three-level comprises a single-phase H-bridge convectional inverter, one bidirectional switch, and two capacitors acting as voltage divider formed by C_1 and C_2 as shown in fig. 1. Furthermore, Four-level comprises a single-phase H-bridge convectional inverter, two bidirectional switches, and three capacitors acting as voltage divider formed by C_1 , C_2 and C_3 as shown in fig. 2. An Improved single-phase N -level inverter needs $(N + 2)$ main switches, 4 main diodes, $4(N - 2)$ clamping diodes, $(N - 1)$ DC bus capacitor / isolated supplies and no flying capacitor. In general

the total number of circuit components used in a given level is represented by $(6N - 3)$. This topology can be extended to any number of levels by increasing the number of capacitor banks and bidirectional switches. The modified H-bridge inverter topology is significantly advantageous over other inverter topologies because of the following facts [11]:

1. It contains less power diodes.
2. It contains less power switches.
3. It contains less capacitor, when compared with inverters of the same number of levels.
4. Equal voltage balances on the power switches.

Proposed improved multilevel inverter topology can be discussed under single-phase structures. Figs. 1-2 show single-phase three-level and four-level improved inverter structures with

S/N	S ₁	S ₂	S ₃	S ₄	S ₅	V _a	V _b	V _{ab}
1	ON	ON	OFF	OFF	OFF	V _{dc}	0	V _{dc}
2	OFF	ON	OFF	OFF	ON	V _{dc} /2	0	V _{dc} /2
3	OFF	ON	OFF	ON	OFF	0	0	0
4	ON	OFF	ON	OFF	OFF	V _{dc}	V _{dc}	0
5	OFF	OFF	ON	OFF	ON	0	V _{dc} /2	-V _{dc} /2
6	OFF	OFF	ON	ON	OFF	0	V _{dc}	-V _{dc}

asynchronous motor as load.

3.1 Single-phase three-level structure of Proposed Inverter Topology

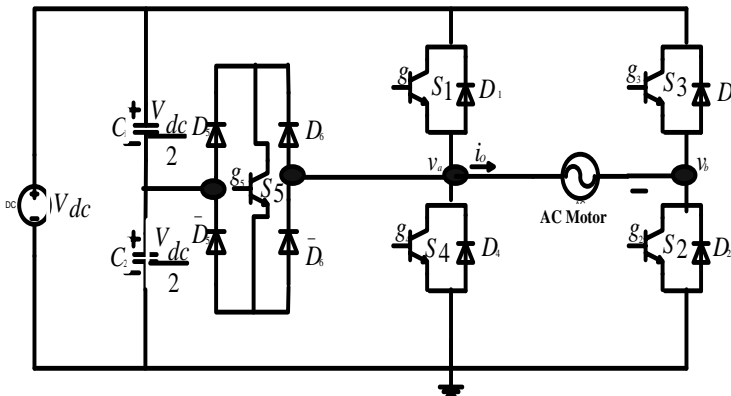


Fig. 1 Power circuit for proposed Single-phase three-level inverter.

The proposed inverter's operation can be divided into five switching states as shown in fig. 1 above and in table 1 below as

$(V_{dc}, V_{dc}/2, 0, -V_{dc}/2, -V_{dc})$. The required three-level or five staircase of output voltage were generated as follows: (1) Mode 1 Operation: To obtain the maximum positive output voltage (V_{dc}) S₁ is ON, connecting the load positive terminal to V_{dc} and S₂ is ON connecting the load negative terminal to ground. All other switches are off; the voltage applied to the load terminal is V_{dc} , (2) Mode 2 Operation: To obtain half positive output voltage ($V_{dc}/2$); the bidirectional

switch S₅ is ON connecting the load positive terminal and S₂ is ON connecting the load negative terminal to ground. All other controlled switches are OFF; the voltage applied to the load terminals is $V_{dc}/2$, (3)

Mode 3 Operation: Zero output: This level can be produced by two switching combinations; switches S₄ and S₂ ON, or S₁ and S₃ are ON and all other controlled switches are OFF; this connection disconnects load terminal from the supplied voltage and no-load current flows, (4) Mode 4 Operation: To obtain one-half negative output ($-V_{dc}/2$); The

bidirectional switch S₅ is ON, connecting the load positive terminal, and S₃ is ON connecting the load Negative terminal to V_{dc} . All other controlled switches are OFF; the voltage applied to the load terminal becomes $-V_{dc}/2$ and, (5) Mode 5 Operation:

To obtain the maximum negative output ($-V_{dc}$): S₃ is ON connecting the load negative terminal to V_{dc} and S₄ is ON connecting the load positive terminal to ground. All other controlled switches are OFF; the voltage applied to the load terminals is $-V_{dc}$. Furthermore, the inverter output voltage, V_{ab} can be computed using the formulae

$$V_a - V_b.$$

TABLE 1
 OUTPUT VOLTAGE SWITCHING PATTERN

From fig. 2 below, the pulse width modulation can be generated by comparing the rectified sinusoidal signal, V_{ref} , with the two triangular carrier signals, V_{tri1} and V_{tri2} placed above zero axis, the switching signals g_1 through g_5 of three-level inverter are derived from the use of basic logic gates in equation

(1). Equation (1) gives the general logical operations for three-level inverter circuit control.

$$\left. \begin{aligned}
 & \text{if } ((V_{ref} > V_{tri1} \text{ AND SIN} > 0) \text{ OR } (V_{tri2} > V_{ref} \text{ AND SIN} < 0)); g_1: \text{ON else OFF}; V_a = V_{dc} \\
 & \quad \text{if } (\text{SIN} > 0); g_2: \text{ON else OFF}; V_b = 0 \\
 & \quad \text{if } (\text{SIN} < 0); \text{ON else OFF}; V_b = V_{dc} \\
 & \text{if } ((V_{ref} > V_{tri1} \text{ AND SIN} < 0) \text{ OR } (V_{tri2} > V_{ref} \text{ AND SIN} > 0)); g_4: \text{ON else OFF}; V_a = 0 \\
 & \quad \text{if } ((V_{ref} < V_{tri1}) \text{ AND } (V_{tri2} < V_{ref})); g_5: \text{ON else OFF}; V_a = \frac{V_{dc}}{2}
 \end{aligned} \right\} (1)$$

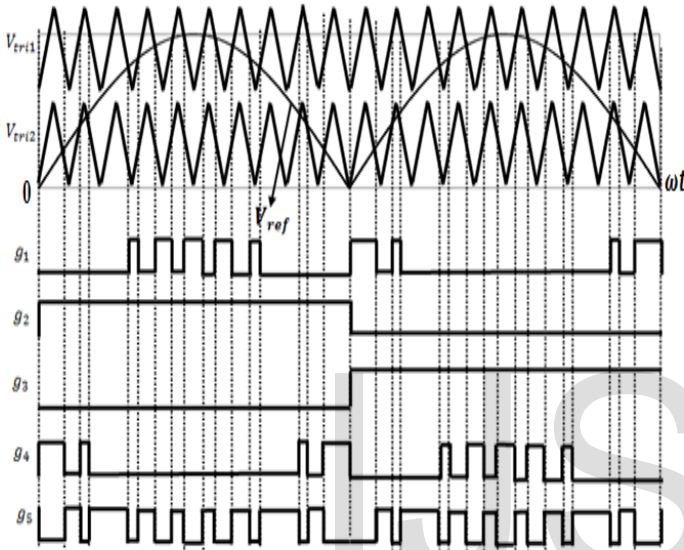


Fig. 2 Switching pattern of the proposed single-phase, three-level PWM inverter.

3.2 Single-phase four-level structure of Proposed Inverter Topology

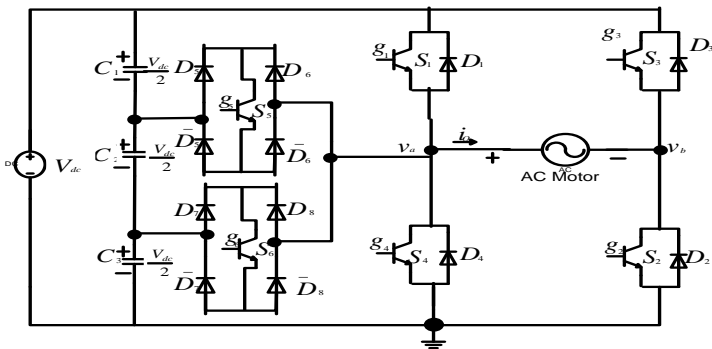


Fig. 3 Power circuit for Single-phase, four-level Improved Inverter Topology.

The proposed inverter's operation as shown in fig. 3 gives seven steps output voltage as $(V_{dc}, \frac{2V_{dc}}{3}, \frac{2V_{dc}}{3}, 0, -\frac{2V_{dc}}{3}, -\frac{2V_{dc}}{3}, -V_{dc})$. The above circuit contains a conventional H-bridge inverter and two bidirectional switches. This utilizes

three carrier signals with rectified modulation signal to give four-level output voltage.

4 ASYNCHRONOUS MOTOR DRIVE

Synchronous speed of Asynchronous Motor varies directly proportional to the supply frequency. Hence, by changing the frequency, the synchronous speed and the motor speed can be controlled below and above the normal full load speed. The voltage induced in the stator, E is directly proportional to the product of slip frequency and air gap flux. The Asynchronous Motor terminal voltage can be considered proportional to the product of the frequency and flux, if the stator voltage is neglected. Any reduction in the supply frequency without a change in the terminal voltage causes an increase in the air gap flux. Asynchronous motors are designed to operate at the knee point of the magnetization characteristic to make full use of the magnetic material. Therefore the increase in flux will saturate the motor. This will increase the magnetizing current, distort the line current and voltage, increase the core loss and the stator copper loss, and produce a high pitch acoustic noise. While any increase in flux beyond rated value is undesirable from the consideration of saturation effects, a decrease in flux is also avoided to retain the torque capability of the motor. Therefore, the pulse width modulation (PWM) control below the rated frequency is generally carried out by reducing the machine phase voltage, V, along with the frequency in such a manner that the flux is maintained constant. Above the rated frequency, the motor is operated at a constant voltage because of the limitation imposed by stator insulation or by supply voltage limitations [1]. In this paper split-phase single-phase Asynchronous Motor is used as inverter load throughout the simulation process.

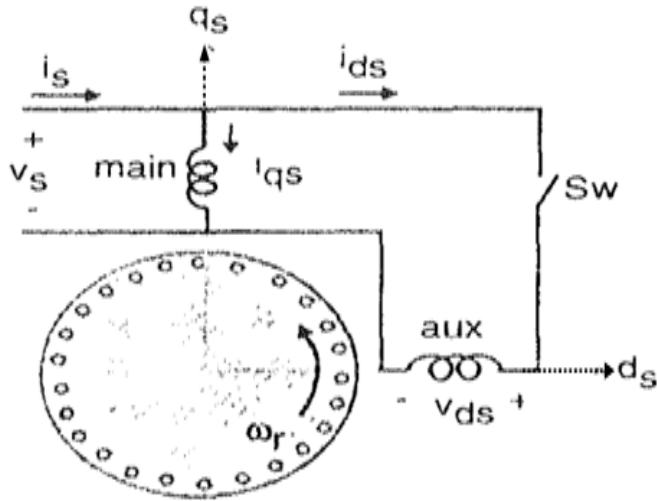


Fig. 4 Split-phase Single-phase Asynchronous Motor.

A three-phase symmetrical induction motor upon losing one of its stator phase supplies while running may continue to operate as essentially a single-phase motor with the remaining line-to-line voltage across the other two connected phases. When the main winding coil is connected in parallel with ac voltage, as in the split-phase single-phase asynchronous motor of fig. 4, the current of the auxiliary winding, i_{ds} , leads i_{qs} of the main winding. For even a larger single-phase induction motor, that lead can be further increased by connecting a capacitor in series with the auxiliary winding, this arrangement brings about a Capacitor-start single-phase asynchronous motor. Fig. 4 shows that the motor has two windings: the main (running) winding and the auxiliary (starting) winding. This motor is modeled in two parts: Electrical part which is represented by a fourth-order state-space model and, mechanical part which is represented by second-order system. All electrical variables and parameters are referred to the stator. This is indicated by the prime signs in the machine equations given below. All stator and rotor quantities are in the stator reference frame (d-q frame).

Electrical System Part Analysis:

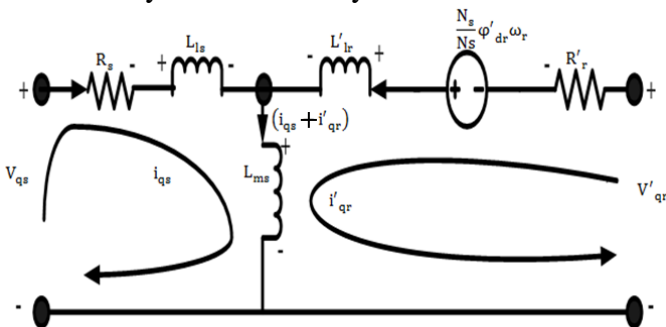


Fig. 5 Main winding (q-axis) circuit diagram

$$V_{qs} = R_s i_{qs} + \frac{d}{dt} \Phi_{qs} \quad (2)$$

Where, $\Phi_{qs} = (L_{ls} + L_{ms})i_{qs} + L_{ms}i'_{qr}$

$$V'_{qr} = R'_r i'_{qr} + \frac{d}{dt} \Phi'_{qr} - \frac{N_s}{N_r} \omega_r \Phi'_{dr} \quad (3)$$

Where, $\Phi'_{qr} = (L'_{lr} + L_{ms})i'_{qr} + L_{ms}i_{qs}$

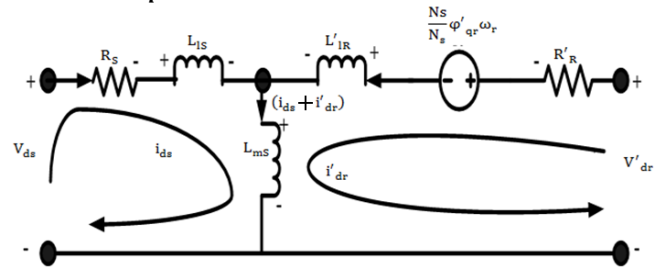


Fig. 6 Auxiliary winding (d-axis) circuit diagram

$$V_{ds} = R_s i_{ds} + \frac{d}{dt} \Phi_{ds} \quad (4)$$

Where, $\Phi_{ds} = (L_{ls} + L_{ms})i_{ds} + L_{ms}i'_{dr}$

$$V'_{dr} = R'_r i'_{dr} + \frac{d}{dt} \Phi'_{dr} + \frac{N_s}{N_r} \omega_r \Phi'_{qr} \quad (5)$$

Where, $\Phi'_{dr} = (L'_{lr} + L_{ms})i'_{dr} + L_{ms}i_{ds}$

$$T_e = p \left(\frac{N_s}{N_r} \Phi'_{qr} i'_{dr} - \frac{N_s}{N_r} \Phi'_{dr} i'_{qr} \right) \quad (6)$$

Mechanical System part Analysis

$$\frac{d}{dt} \omega_m = \frac{1}{2H} (T_e - F\omega_m - T_L) \quad (7)$$

$$\frac{d}{dt} \theta_m = \omega_m \quad (8)$$

It is vital to note that the reference frame fixed in the stator is used to convert voltages and currents to the dq frame, this enables for easier model analysis of the system. The following relationships describe the ab-to-dq frame transformations applied to the single phase asynchronous machine.

$$\begin{bmatrix} f_{qs} \\ f_{ds} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} f_{as} \\ f_{bs} \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} f_{qr} \\ f_{dr} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ -\sin\theta_r & -\cos\theta_r \end{bmatrix} \begin{bmatrix} f_{ar} \\ f_{br} \end{bmatrix} \quad (10)$$

The variable f can represent either voltage, current or flux linkage. The single phase asynchronous machine block parameters as shown in fig. 7 are defined as follows (all quantities are referred to the stator):

TABLE 2
 DEFINITION OF SYMBOLS IN
 ASYNCHRONOUS MOTOR MODEL

Para- meters	Definitions	units
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R_s, L_{ls}	Main winding stator resistance and leakage inductance	Ω and H
R_s, L_{ls}	Auxiliary winding stator resistance and leakage inductance	
R'_r, L'_{lr}	Main winding rotor resistance and leakage inductance	
R'_R, L'_{lR}	Auxiliary winding rotor resistance and leakage inductance	
L_{ms}	Main winding magnetizing inductance	H
L_{mS}	Auxiliary winding magnetizing inductance	
V_{as}, i_{as} V_{bs}, i_{bs} V_{qs}, i_{qs} V_{ds}, i_{ds} V'_{qr}, i'_{qr} V'_{dr}, i'_{dr}	Main winding stator voltage and current Auxiliary winding stator voltage and current q-axis stator voltage and current d-axis stator voltage and current q-axis rotor voltage and current d-axis rotor voltage and current	V and A
ϕ_{qs}, ϕ_{ds}	Stator q and d-axis fluxes	V.s
ϕ'_{qr}, ϕ'_{dr}	Rotor q and d-axis fluxes	V.s
ω_m	Rotor angular velocity	Rad/s ec
θ_m	Rotor angular position	rad
p	Number of pair poles	
ω_r	Electrical angular velocity ($\omega_r * p$)	Rad/s ec
θ_r	Electrical rotor angular position ($\theta_r * p$)	rad
T_e	Electromagnetic torque	Nm
T_m	Shaft mechanical torque	Nm
J	Combined rotor and load inertia coefficient. Set to infinite to simulate locked rotor	Kg.m ²
F	Combined rotor and load viscous friction coefficient	Nms
H	Combined rotor and load inertia constant. Set to infinite to simulate locked rotor	sec
Ns	Number of auxiliary winding's effective turns	turns
N_s	Number of main winding's effective turns	Turns

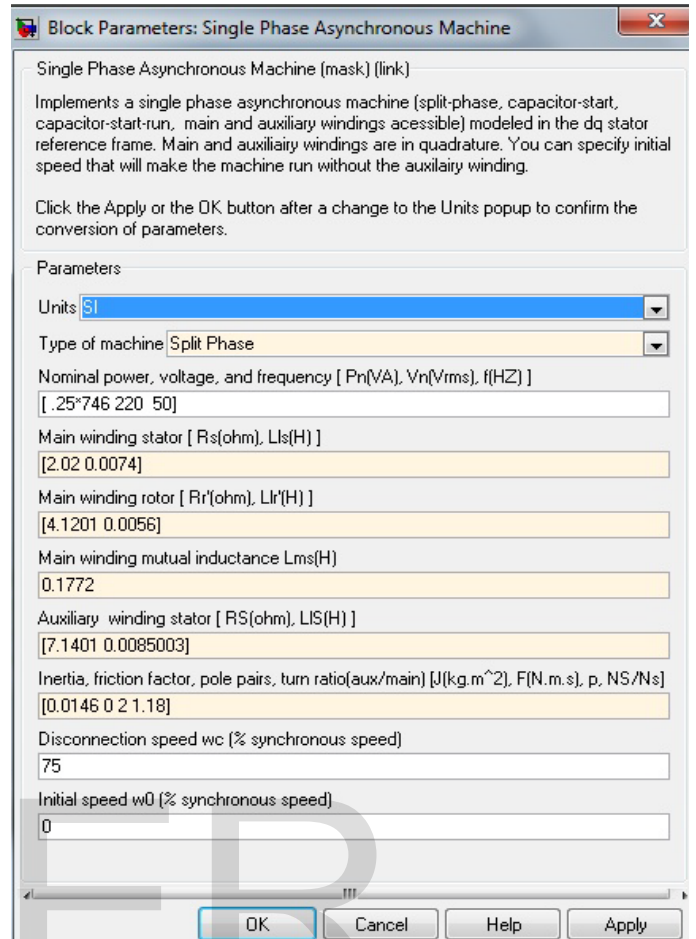


Fig. 7 Split-phase single-phase asynchronous motor parameter.

5 SIMULATION MODEL AND RESULTS

Multilevel inverter fed asynchronous motor drive inverter is implemented in MATLAB SIMULINK which is shown in Fig. 8. The MATLAB SIMULINK model of an Improved Single-phase Multilevel inverter using three-level configuration topology is shown in Fig. 8.

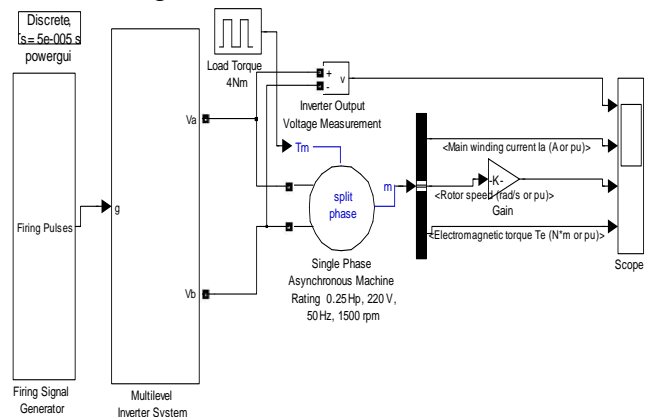


Fig. 8 Matlab/Simulink model of Multilevel Asynchronous Motor drive.

An Improved single-phase three-level inverter output voltage after feeding to asynchronous motor is shown in Fig. 9. The stator main winding output current with respect to single-phase is shown in Fig. 11. The Variation in speed is shown in Fig. 12. The machine starts at no load and then at $t=2.0$ sec, once the machine has reached its steady state, the load torque is increased to its nominal value (4 N.m) in 1.0 sec. The speed increases and settles at 1500 rpm without torque load and drops to 1450 rpm when loaded with torque load. The Electromagnetic torque is shown in Fig. 13. The Fast Fourier Transform (FFT) analysis is done for the output voltage and stator main winding current and the corresponding spectrum is shown in Fig. 14 and Fig. 15 respectively. It can be seen that the magnitude of fundamental voltage for three-level inverter fed asynchronous motor drive is 193.2 Volts. The total harmonic distortion is 4.41 percent and the magnitude of fundamental current is 26.63 Amperes. The total harmonic distortion is 1.25 percent.

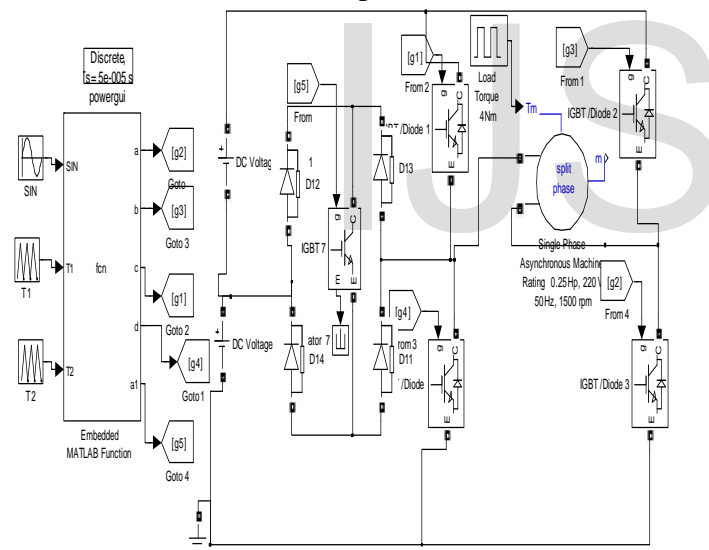


Fig. 9 Matlab/Simulink model of An Improved Single-phase Three-level Inverter.

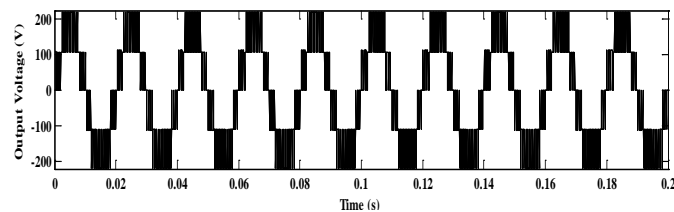


Fig. 10 Single-phase three-level inverter output Voltage.

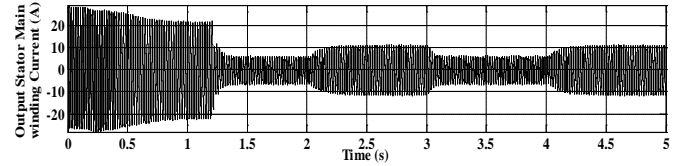


Fig. 11 Single-phase three-level inverter output Stator Main winding current.

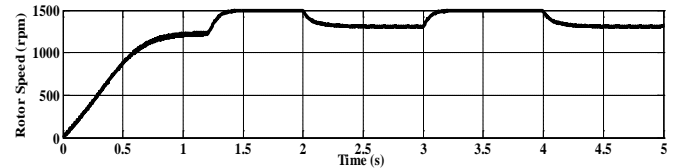


Fig. 12 Variation in speed

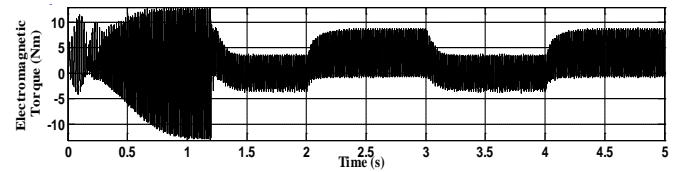


Fig. 13 Variation in Electromagnetic torque

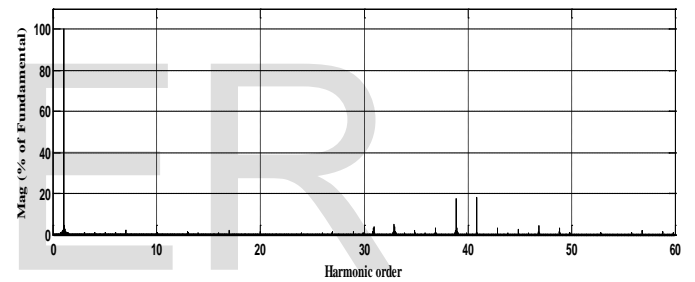


Fig. 14 FFT analysis of Voltage

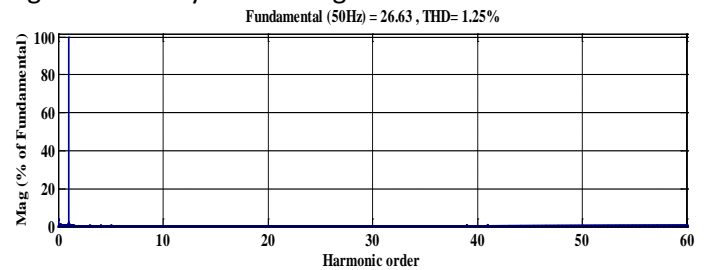


Fig. 15 FFT analysis of Current

The MATLAB SIMULINK model of An Improved Single-phase of four-level Inverter configuration is shown in Fig. 16

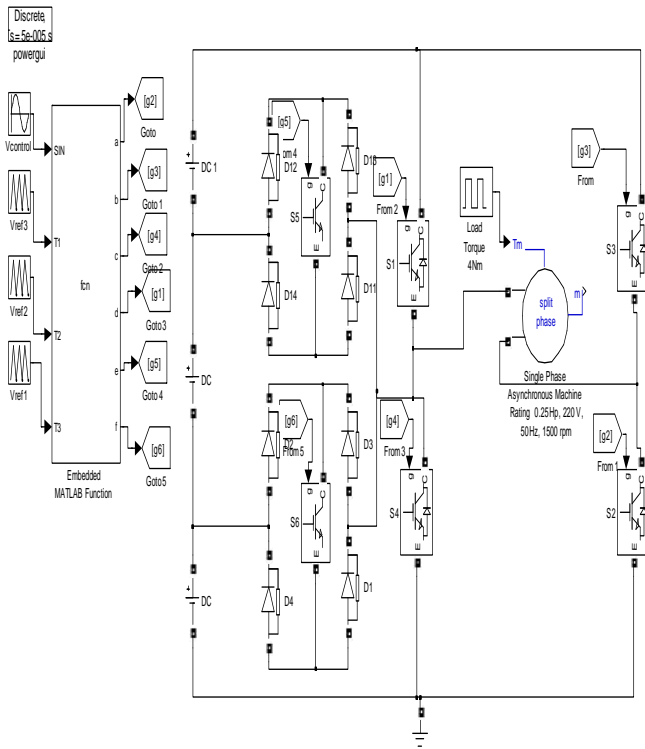


Fig. 16 Matlab/Simulink model of An Improved single-phase four-level Inverter.

An Improved single-phase four-level inverter output voltage after feeding to asynchronous motor is shown in Fig. 17. The output stator main winding current with respect to single-phase is shown in Fig. 18. The Variation in speed is shown in Fig. 19. The speed increases and settles at 1500 rpm without torque load and drops to 1450 rpm when loaded with torque load of 4 Nm. The Electromagnetic torque is shown in Fig. 20. The Fast Fourier Transform (FFT) analysis is done for the voltage and output stator main winding current and the corresponding spectrum is shown in Fig. 21 and Fig. 22 respectively. It can be seen that the magnitude of fundamental voltage for four-level inverter fed asynchronous motor drive is 193.6 Volts. The total harmonic distortion is 2.55 percent and the magnitude of fundamental current is 26.7 Amperes. The total harmonic distortion is 1.12 percent.

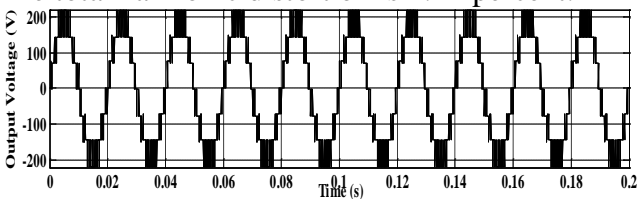


Fig. 17 Single-phase four-level inverter output Voltage.

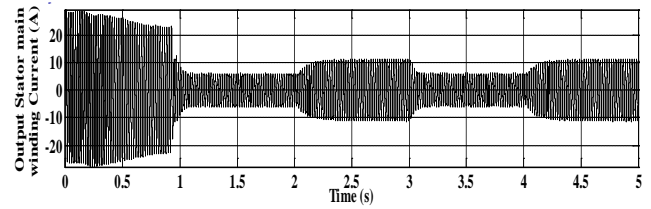


Fig. 18 Single-phase four-level inverter output Stator Main winding current.

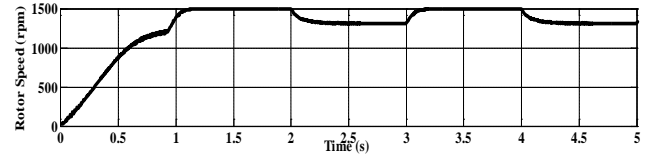


Fig. 19 Variation in speed

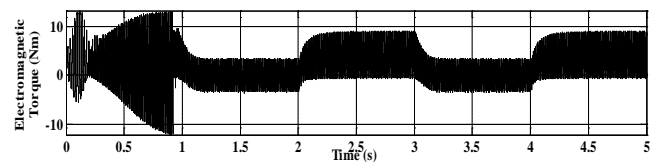


Fig. 20 Variation in Electromagnetic torque

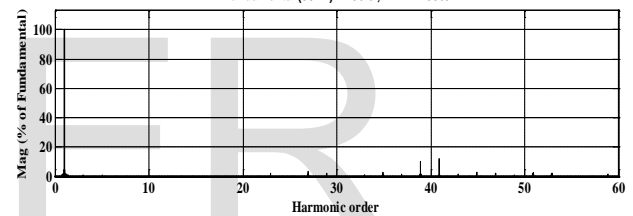


Fig. 21 FFT analysis of Voltage

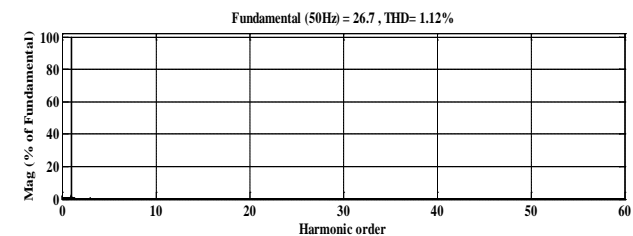


Fig. 22 FFT analysis of Current

The results are tabulated in Table 3 below.

TABLE 3
 THD ANALYSIS OF THREE-LEVEL AND FOUR-LEVEL IMPROVED INVERTER WHEN FED TO ASYNCHRONOUS MOTOR DRIVE

Parameters	Proposed Improved Multilevel Inverter	
	Three-level Inverter	Four-level Inverter
Voltage Level (V)	193.6	193.5
THD for Voltage (%)	4.41	2.55

Current Level (A)	26.63	26.7
THD for Current (%)	1.25	1.12

6 CONCLUSION

Three-level and Four-level Improved inverter fed asynchronous motor drive are simulated using the blocks of Matlab/Simulink/SimPowerSystems. The results of three-level and four-level systems are compared. It is observed that the total harmonic distortion produced by the four-level inverter system is less than that of three-level inverter fed drive system. Therefore the heating due to four-level inverter system is less than that of three-level inverter fed drive system. The switching losses due to four-level inverter system is higher than that of three-level inverter fed system because of high number of power switches involved in the design. The simulation results of voltage, current, electromagnetic torque, speed and spectrum are presented. This drive system can be used in industries where adjustable speed drives are required to produce output with reduced harmonic content. The scope of this work is the modeling and simulation of three-level and four-level inverter fed asynchronous motor drive systems. Cascaded Hybrid bridge multilevel topology will be used to drive the asynchronous motor in future work. Four-level or higher level inverter system is a viable alternative since it has better performance.

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