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A Multilevel Inverter Configuration for Open End Winding Induction Motor

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***Abstract*—This paper proposes a MLI configuration for open end winding induction motor. An important feature of this configuration is that the number of conducting switches remains the same during each level. The proposed topology reduces the number of DC voltage sources, power switches and diodes. This configuration can extend to higher number levels easily. The performance of proposed MLI is evaluated for an open-end winding induction motor.**

***Index Terms*— Multilevel inverter, Open-End winding induction motor, THD.**

I. INTRODUCTION

The work horse any of modern world is electric motors. There are different types of electric motors like DC motors which include series, shunt and compound motors. AC motors like induction, synchronous, permanent magnet etc. The type of motor used depends on the application. Of all the available motors AC induction motor (IM) contributes 90% of the industrial load [1]. The reason for its popularity is rugged construction, cheaper compared to DC motors for similar power rating, higher torque to weight ratio, better power to cost ratio compared to DC motors, absence of physical contact between rotor and stator giving added safety compared to brushed motor, high speed of operation up to 15000 RPM is possible [4].

The three phase induction motor is classified into slip ring induction motor and squirrel cage induction motor. The application of slip ring induction motor is limited due to cost factor where as squirrel cage induction is widely accepted in industry. The stator windings of squirrel cage induction motor can be connected in either star or delta depending on the type of application. For this purpose the six leads of the IM are brought out. If the six leads are not connected in star or delta and given to three independent AC source phase displaced by 120^o results in open end winding induction motor (OEWIM). This type of configuration has been considered as serious contender for high power application (traction and similar) since the early 1990s [2][3].

The size of the AC motor depends upon the power rating and operating voltage and has the most influence on the performance of the AC electric drive. Also motor influences the selection of other major components of the electric drive system like converters and controllers. For the AC electric drives a combination of DC-DC converters with inverters using PWM strategies are used. However, switching loss and total harmonic distortion (THD) are still relatively high for these proposed schemes [5].

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In recent years multilevel inverters have attained lot of interest. These inverters consist of array of power switches and input voltage source is basically capacitors or batteries. The power switches connects the input to the output such a way that the load sees a stepped waveform. The turning on and off of power switches results in addition of capacitor or battery voltage, which reach high voltage at the output, while the power switches has to withstand lesser voltage [6]. Fig 1 shows a schematic diagram of on phase leg of inverters with different number of levels, for which the action of the power switches is represented by an ideal switch with several position. A two level inverter generates an output voltage with two values (levels) with respect to the terminal of the capacitor (fig 1(a)), while the three level inverter generates three voltages and so on.

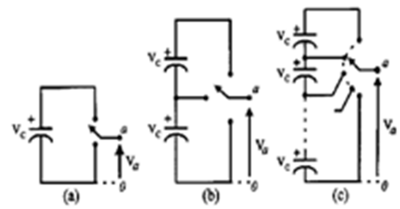


Fig 1. One phase leg of an inverter with (a) two levels, (b) three levels, and (c) n levels

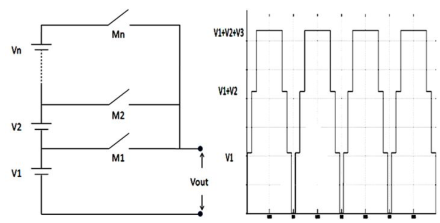


Fig 2. (a) Level generator module (b) Typical output wave forms of LGM

Multilevel inverters are finding increased application in the area of electric drives, because of advantages it provides compared to the two level PWM inverters. Objective of multilevel inverter is to synthesis stepped output waveform which approaches sinusoidal waveform. With increased number of steps it is expected that total harmonic distortion in output waveform decreases [7].

Multilevel inverters originally developed for utility applications such as static var compensators [8]. In such system only reactive power flows between the converter and the system where as the converter must handle real power flow in both directions in case of motor drives. The use of cascaded and diode clamped MLI for large vehicles like trucks and military vehicles have been proposed [9]. The major drawback in this type of MLI as the number voltage levels increases the number of power switches also increases resulting in increased conduction loss. The control algorithm that generates the gate pulse for MLI becomes very complex with increase in voltage levels. The number of isolated gate drivers required for controlling power devices such as MOSFETs or IGBTs also increases leading to circuit complexity.

In this paper, a MLI with constant number of conducting switch with separate DC sources is proposed as inverter for electric drives with open end winding induction motors. This configuration has reduced switch count as compared with conventional multilevel inverters like cascaded and diode clamped and also number of conducting switch remains constant with increase in levels. The control technique for generating gate pulses is also discussed for this configuration. The feasibility of proposed configuration has been proved by simulation.

II. MLI with Constant Number of Sonducting Switch and Operation

The minimum and maximum voltage that can be obtained with this arrangement is where Vs is the input DC voltage.

$$V_{out(min)} = 0 \qquad (1)$$
$$V_{out(\max)} = pV_s \qquad (2)$$

If $C_j(t)$, represents the conduction state of jth branch of the LGM at any instant of time t and j = 1,2,3 … p. Then C_j can take value '1' which represent ON state and '0' which represent OFF state of the branch. The output voltage of the level generating module can then be expressed as

$$V_{out}(t) = V_{s1}C_1(t) + V_{s2}C_2(t) + \cdots + V_{sp}C_p \qquad (3)$$

The output wavefc … case voltage waveform with positive polarity, which is a unidirectional stepped waveform. The LGM is then interfaced to H-bridge converter, which alternates the unidirectional stepped waveform obtained from LGM to provide a positive or negative staircase waveform at the output. The full bridge converter consists of fewer unidirectional switches. The configuration is shown in Fig 3a. When switch B1 and B2 is turned on the direction of current is positive in the load and when the switch B3 and B4 are turned on the direction of current is reversed in load. The output thus obtained is shown in Fig 3b. The positive output voltage at any instant on the load is

$$V_{out}(t)^{+} = [V_{s1}C_1(t) + V_{s2}C_2(t) + \cdots + V_{sp}C_p](B_1(t)\cdot B_2(t)) \qquad (4)$$

$$V_{out}(t)^{-} = [V_{s1}C_1(t) + V_{s2}C_2(t) + \cdots + V_{sp}C_p](B_3(t)\cdot B_4(t)) \qquad (5)$$

and overall at any instant is given by

$$V_{out}(t) = V_{out}(t)^{+} + V_{out}(t)^{-} \qquad (6)$$

It is noticeable that only one switch turns on in different operation modes of the LGM and also, both switches B1 and B4 (or B2 and B3) cannot be simultaneously turned on (expect state 1 in Table I) because of a short circuit occurrence across DC voltage sources and then the voltage V_{out} would be produced. Table I summarizes the values of the output voltage of a LGM and corresponding H-bridge converter for different state of switches M1, M2, . . . , Mn, B1, . . . , B4. State conditions 1 and 0 means that the switch is on and off, respectively. For simplicity, the on-state voltage drops of switches have been neglected. As it can be seen, 2n + 1 different value can be obtained for V_{out}.

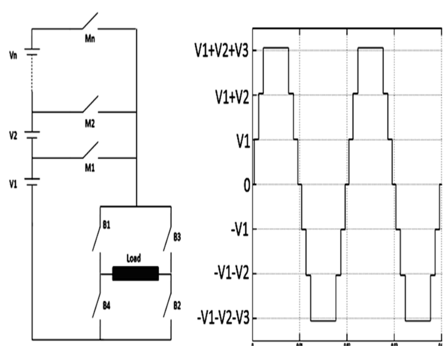


Fig. 3. (a) H-bridge interfaced to LGM. (b) Typical output waveforms of interfaced circuit with three voltage source

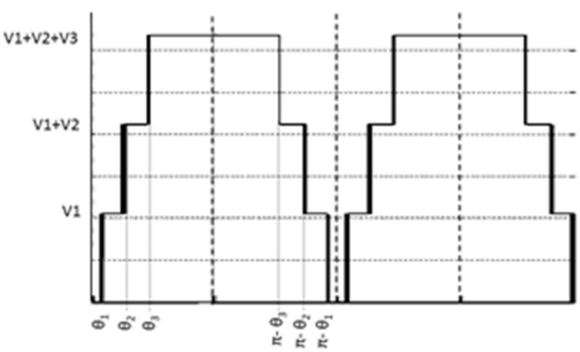


Fig 4. LGM output with switching angles

The number of switching angles required is equal to the number of independent DC sources. Therefore number of switching angles required is given by

$$Sw_{angle} = p = \frac{N-1}{2} \qquad (7)$$

magnitude of switching angle is

$$\theta_j = arcsin\left(\frac{2j-1}{N-1}\right) \qquad (8)$$

where j = 1,2, ….., p

The gate pulse pattern obtained for various value of θ_j is shown in Fig 4. It can be seen from Fig 4 that other angles can be easily computed for θ_1, θ_2, … etc. Fig 5 gives the gate pulse pattern for different switches in various branches of level generating module.

III. MLI CONFIGURATION FOR OEWIM

An OEWIM consists of six terminals, two terminals for each phase. The configuration of MLI for 3-phase OEWIM is shown in Fig 6. MLI drives the OEWIM. The configuration can also be operated in regenerative mode where the stored energy in motor supplies energy to energy storage systems like battery or capacitors with MLI operating in regenerative mode.

The configuration in Fig 6 consists for three converters namely converter-1, converter-2 and converter-3. Converter-1 gives phase A output, converter-2 gives phase B output, converter-3 gives phase C output. Each of the phases is displaced by 120^o. The three phase output of the converter is shown in Fig 7.

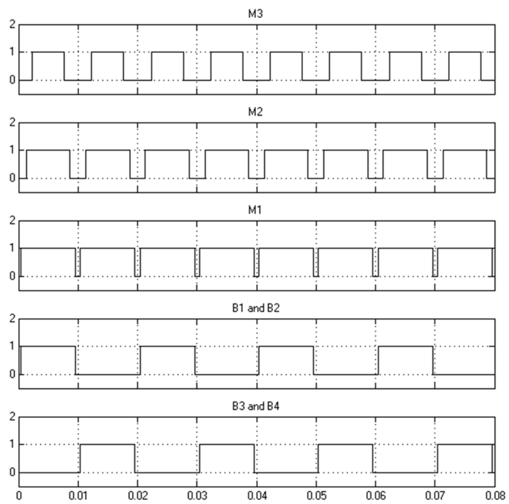


Fig 5. Gate Pulse pattern

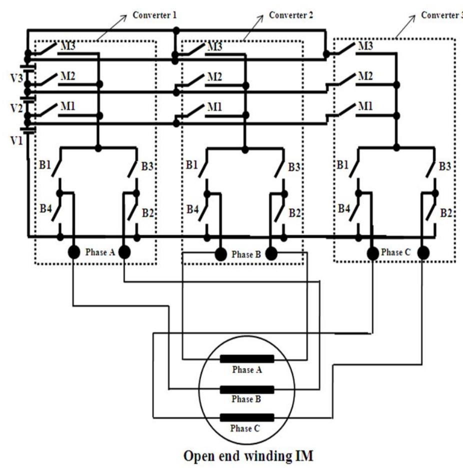


Fig 6. MLI Configuration for Open end winding IM

IV. RESULTS

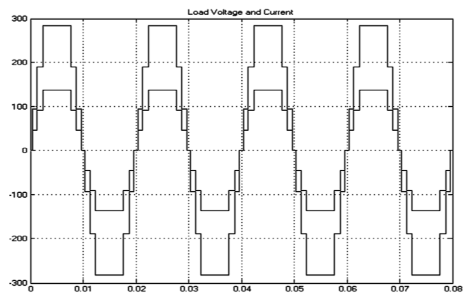
Computer simulations are carried out for the proposed strategy using MATLAB for constant conducting MLI fed OEWIM drive configuration with equal DC-link voltages. The DC source voltage of 110 volts is given for each branch of level generating module of the proposed MLI for OEWIM where 330 volt DC is the resultant voltage given to the system. The modeling parameters of Induction motor are given in the Table II. The load voltage and current waveform for resistive load is shown in Fig 7 and for inductive load is shown in Fig 8. The voltage and current spectrum is shown in Fig 9. It is seen from Fig 9 that the total harmonic distortion in voltage waveform is 15.21% and that of current waveform is 7.12% for inductive load of 5.8mH.

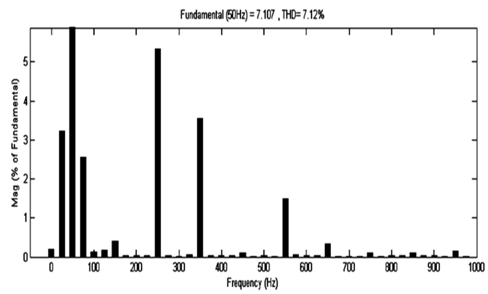
To understand the performance of OEWIM simulation were performed for a voltage of 415 V 3 - phase stepped sine wave provided by the MLI. The load torque of 12 Nm is applied to the OEWIM for specifications given in Table 2 for 1 second. The simulated rotor and stator current waveforms are shown in Fig 11. Fig 12 shows the variation of speed and electromagnetic torque developed by the OEWIM. It is observed that motor takes 0.12 seconds to reach steady state speed. The peak value of electromagnetic torque is 43 Nm. The steady state electromagnetic torque has some amount of ripple in it and it is found to vary between 11 Nm and 13 Nm. The ripple in electromagnetic torque does not reflect on motor speed due to inertia of motor.

To understand the performance of the induction motor with variation of load torque simulation were carried out for three seconds. Initially a load torque of 12 Nm is applied for 1 sec and then it increased to 24 Nm from 1 sec to 2 seconds and from 2 seconds to 3 seconds it is reduced to 12 Nm. Fig 12 gives rotor and stator current waveform with respect to variation of load torque. Fig 13 gives the variation of motor speed and electromagnetic torque due to variation of load torque. It is seen from Fig 13 that motor speed reaches steady state after 0.12 seconds and remains at 1500 RPM till load torque is increased to 24 Nm at 2 seconds. When load torque is increased motor speed drops from 1500 RPM to 1380 RPM and when the load is removed motor speed increases to 1500 RPM.

TABLE II MOTOR PARAMETERS

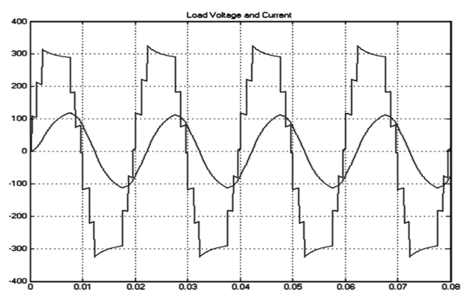
stator inductance (Ls)	0.005839
Rotor inductances (Lr)	0.005839
Mutual inductances (Lm)	0.0068
Stator resistance (Rs)	2.08
Rotor resistance (Rr)	1.19

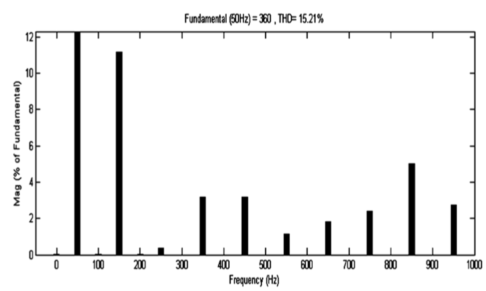




(a)

Fig 7. Load voltage and current waveforms for resistive load

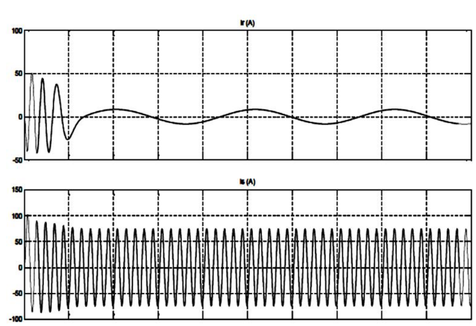




(b)

Fig 8. Load and Current waveform for inductive load

Fig 9. (a) Current and (b) Voltage Spectrum



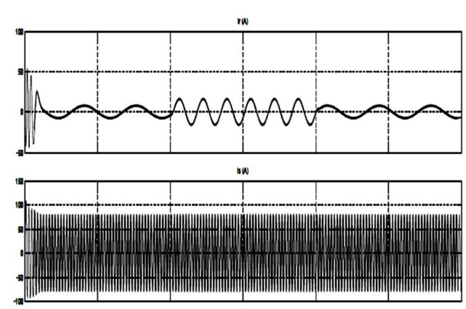


Fig 10. Rotor and Stator current waveforms for stepped 7-level voltage waveform

Fig 12. Rotor and Stator current with changes in load torque

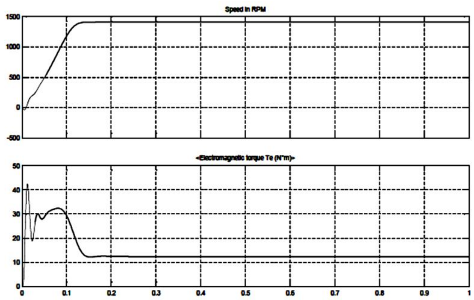


Fig 11. Variation of speed and Electromagnetic torque with respect to time for stepped 7-level voltage waveform

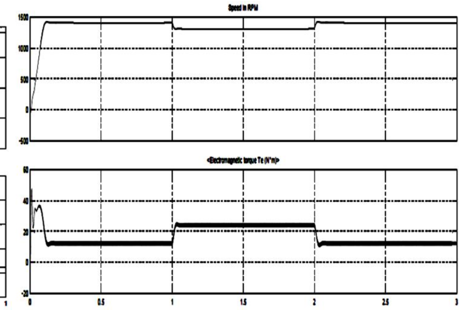


Fig 13. Variation of speed and electromagnetic torque with changes in load torque

V. CONCLUSION

A configuration of multilevel inverter with constant number of conducting switches has been proposed for open end winding induction. The operation of proposed inverter and calculation of conducting angles for the proposed configuration has been introduced. The additional level module units can be used to increase the output levels. The performance of the proposed inverter for OEWIM is evaluated through simulation and it is observed that transients in the motor subside by 0.12 seconds as seen in Fig 10 and Fig 11. The THD of the proposed inverter is less and it is around 16.21%.

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