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Performance Evaluation of Flying Capacitor Multilevel Inverter Based Induction Motor Drive

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Abstract— **Multi-level inverters go a long way in overcoming the problems of conventional two level Pulse Width Modulated (PWM) inverters and this is the reason that they have gained so much attention in recent years. This paper presents the performance evaluation of 3-level and 5-level Flying capacitor inverter fed Induction motor drive using Scalar or v/f control technique. This paper compares the performance of the conventional two-level inverter Induction motor drive with multilevel (3-level and 5-level) inverter drive. This paper also presents the comparison of line current total harmonic distortion (THD) variation with frequency for the three inverters considered in this work.**

Keywords— Flying Capacitor Multilevel Inverter (FCMLI), Sinusoidal Pulse Width Modulation (SPWM), Scalar Control, Induction motor, Total Harmonic Distortion (THD).

I. INTRODUCTION

In recent years, industry has begun to demand higher power equipment, which now reaches the megawatt level. Controlled ac drives in the megawatt range are usually connected to the medium-voltage network. Today, it is hard to connect a single power semiconductor switch directly to medium-voltage grids (2.3, 3.3, 4.16, or 6.9 kV). For these reasons, a new family of multilevel inverters has emerged as the solution for working with higher voltage levels [1].

Multilevel inverters include an array of power semiconductors and capacitor voltage sources, the output of which generate voltages with stepped waveforms. The commutation of the switches permits the addition of the capacitor voltages, which reach high voltage at the output, while the power semiconductors must withstand only reduced voltages.

The most attractive features of multilevel inverters are as follows.

1. They can generate output voltages with extremely low distortion and lower dv/dt.
2. They draw input current with very low distortion.
3. They generate smaller common-mode (CM) voltage, thus reducing the stress in the motor bearings. In addition, using sophisticated modulation methods, CM voltages can be eliminated.
4. They can operate with a lower switching frequency.

Majority of industrial drives use ac induction motor because these motors are rugged, reliable, and relatively inexpensive. Induction motors are mainly used for constant speed applications because of unavailability of the variable-frequency supply voltage. But many applications need variable speed operations. Historically, mechanical gear systems were used to obtain variable speed. Recently, power electronics and control systems have matured to allow these components to be used for motor control in place of mechanical gears. These electronics not only control the motor's speed, but can improve the motor's dynamic and steady state characteristics. Adjustable speed ac machine system is equipped with an adjustable frequency drive that is a power electronic device for speed control of an electric machine. It controls the speed of the electric machine by converting the fixed voltage and frequency to adjustable values on the machine side.

High power induction motor drives using classical three - phase converters have the disadvantages of poor voltage and current qualities. To improve these values, the switching frequency has to be raised which causes additional switching losses. Another possibility is to put a motor input filter between the converter and motor, which causes additional weight. A further inconvenience is the limited voltage that can be applied to the induction motor determined by the blocking voltage of the semiconductor switches.

The concept of multilevel inverter control has overcome the problems associated with the conventional two inverter control of induction motor drive.

II. FLYING CAPACITOR MULTILEVEL INVERTER (FCMLI)

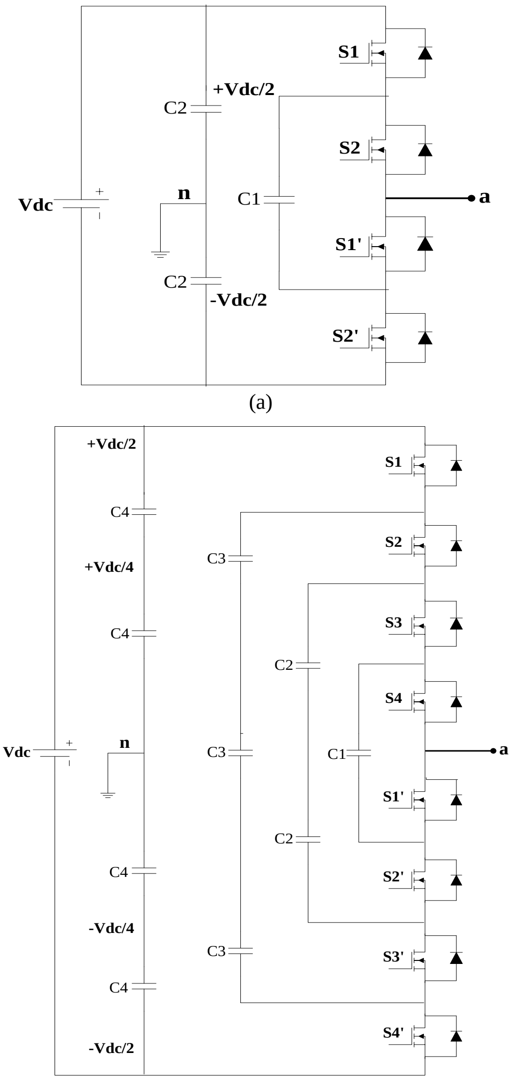
For high voltage application, some problems have been encountered while dealing with the practical control and implementation of main topologies. These include,

1. Voltage unbalances between DC capacitors.
2. Indirect clamping of inner switching devices.
3. Series connected clamping diodes.

To overcome these problems, a multilevel structure with flying capacitors was proposed.

A. Basic Configuration of FCMLI

Fig.1 shows one phase leg of a 3-level and a 5-level Flying capacitor inverters. The circuit has been called the flying capacitor inverter (FCMLI) with independent capacitors clamping the device voltage to one capacitor voltage level.



(a)

(b)

Fig.1 One Phase Leg of (a) 3-Level, (b) 5-Level Flying Capacitor Inverter

The inverter in Fig.1 (a) provides a three-level output across '*a*' and '*n*', i.e., V_{an} = V_{dc}/2, 0, or - V_{dc}/2. For voltage level V_{dc}/2, switches S_1 and S_2 need to be turned on, for - V_{dc}/2, switches S_1' and S_2' need to be turned on and for the 0 level, either pair (S_1, S_1') or (S_2, S_2') needs to be turned on. Clamping capacitor C_1 is charged when S_1 and S_1' are turned on, and is discharged when S_2 and S_2' and are turned on. The charge of C_1 can be balanced by proper selection of the 0-level switch combination.

The voltage synthesis in a five-level capacitor-clamped converter has more flexibility than a diode-clamped converter. Fig.1 (b) shows a five-level flying capacitor inverter.

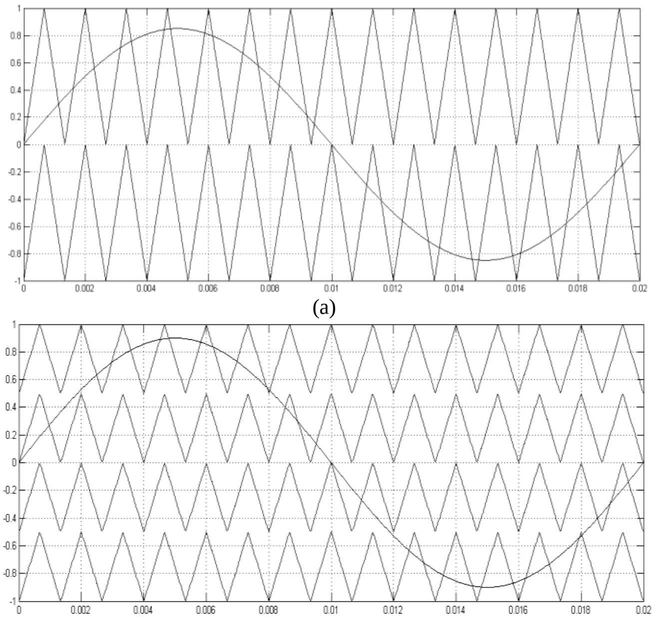
Using Fig.1 (b), the voltage of the five-level phase-leg '*a*' output with respect to the neutral point '*n*', V_{an}, can be synthesized by the following switch combinations.

1. For voltage level V_{an} = V_{dc}/2, turn on all upper switches S_1-S_4.
2. For voltage level V_{an} = V_{dc}/4, there are three combinations:
   a) S_1, S_2, S_3, S_1' (V_{an} = V_{dc}/2 of upper C_4's- V_{dc}/4 of C_1)
   b) S_2, S_3, S_4, S_4' (V_{an} = 3V_{dc}/4 of C_3's- V_{dc}/2 of lower C_4's) and
   c) S_1, S_3, S_4, S_3' (V_{an} = V_{dc}/2 of upper C_4's-3 V_{dc}/4 of C_3's+ V_{dc}/2 of C_2's).
3. For voltage level V_{an} = 0, there are six combinations:
   a) S_1, S_2, S_1', S_2' (V_{an} = V_{dc}/2 of upper C_4's- V_{dc}/2 of C_2's)
   b) S_3, S_4, S_3', S_4' (V_{an} = V_{dc}/2 of C_2- V_{dc}/2 of lower C_4)
   c) S_1, S_3, S_1', S_3' (V_{an} = V_{dc}/2 of upper C_4's- 3V_{dc}/4 of C_3's+ V_{dc}/2 of C_2's- V_{dc}/4 of C_1)
   d) S1, S4, S_2', S_3' (Van = Vdc/2 of upper C4's- 3Vdc/4 of C3's+Vdc/4 of C1)
   e) S2, S4, S_2', S_4' (Van = 3Vdc/4 of C3's- Vdc/2 of C2's+Vdc/4 of C1- Vdc/2 of lower C4) and
   f) S_2, S_3, S_1', S_4' (V_{an} = 3V_{dc}/4 of C_3's- V_{dc}/4 of C_1 - V_{dc}/2 of lower C_4)
4. For voltage level V_{an} = -V_{dc}/4, there are three combinations:
   a) S_1, S_1', S_2', S_3' (V_{an} = V_{dc}/2 of upper C_4's- 3V_{dc}/4 of C_3's)
   b) S_4, S_2', S_3', S_4' (V_{an} = V_{dc}/4 of C_1- V_{dc}/2 of lower C_4's) and
   c) S_3, S_1', S_3', S_4' (V_{an} = V_{dc}/2 of C_2's- V_{dc}/4 of C_1- V_{dc}/2 of lower C_4's).
5. For voltage level V_{an} = -V_{dc}/2, turn on all lower switches S_1'-S_4'.

B. Modulation Scheme

In this paper sinusoidal pulse width modulation (SPWM) strategy is employed. Unlike in two-level inverter modulation, here a number ((n-1) for n-level) of triangular carrier signals are compared with a controlled sinusoidal modulating signal. The switching rules for the switches are decided by the intersection of the carrier waves with the modulating signal.

Fig.2 shows the SPWM signals for 3-level and 5-level inverters. The modulating signal of each phase is displaced from each other by 120°. All the carrier signals have same frequency (f_c) and amplitude but they are shifted in their magnitude (Level-Shifted).



(a)

(b)

Fig.2 SPWM Signals for (a) 3-level (b) 5-level Inverter

III. SCALAR CONTROL OF INDUCTION MOTOR IV.

Scalar control of Induction Machine is one of the very useful and simple techniques of speed controlling. Here, the V/f ratio is maintained constant in order to get constant torque over the entire operating range. In this paper main focus is on multilevel inverter, so scalar control is used for evaluating the performance of induction motor drive.

The torque developed by the motor is directly proportional to the magnetic field produced by the stator. So, the voltage applied to the stator is directly proportional to the product of stator flux and angular velocity. This makes the flux produced by the stator proportional to the ratio of applied voltage and frequency of supply. By varying the frequency, the speed of the motor can be varied. Therefore, by varying the voltage and frequency by the same ratio, flux and hence, the torque can be kept constant throughout the speed range.

Approximates *constant air-gap flux* when E_{ag} is large

$$E_{ag} = kf\Phi_{ag}$$

$$\Phi_{ag} = constant = \frac{E_{ag}}{f} \approx \frac{V}{f}$$

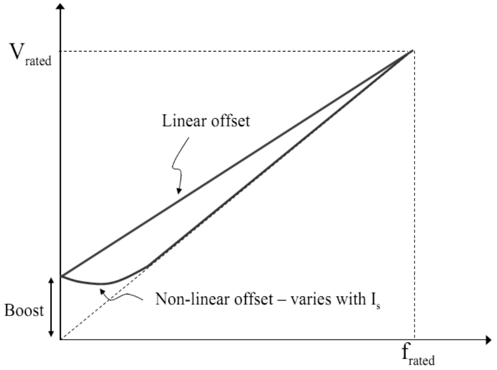


Fig.3 Voltage Vs Frequency Characteristics in V/f Control

Fig.3 shows the voltage Vs frequency characteristics in v/f control, which also includes the modified characteristics after the voltage boost at low speeds.

Fig.4 shows the closed-loop v/f control scheme for multilevel inverter fed induction motor drive.

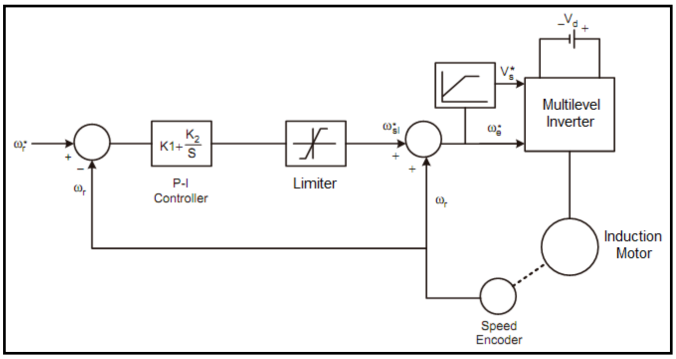


Fig.4 Closed-Loop Speed Control of Induction Motor Using V/f principle

Here, the motor speed is compared with the command speed, and the error generates the slip frequency (ω_{sl}*) command through a P-I compensator and limiter. The slip is added to the feedback speed to generate the frequency and voltage command as shown. Because slip is proportional to torque at constant airgap flux, the scheme can be considered as torque control within a speed control loop. The machine can accelerate/decelerate within the slip limit (i.e., the current limit).

V. PERFORMANCE EVALUATION OF INDUCTION MOTOR DRIVE

In this paper the performance of 2-level PWM inverter and 3-level, 5-level Flying capacitor inverters fed induction motor drive was evaluated.

Fig.5 shows the generalized Simulink model for all types of inverters fed induction motor drive. The model was used to evaluate all inverters fed induction motor drive with corresponding changes in the inverter subsystem block and in the switching control block.

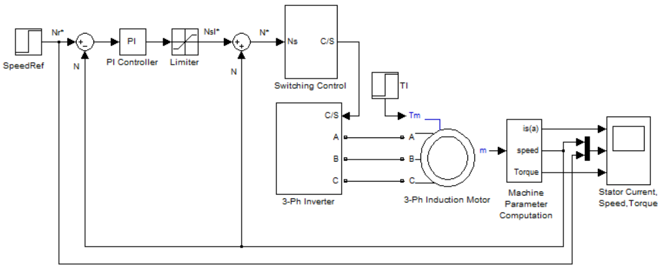


Fig.5 Generalized Simulink Model for Inverter fed Induction Motor Drive

The 3-Phase Induction motor used has the following rating:

Power	:	20 HP (15KW)
Voltage	:	400 Volts
Frequency	:	50 Hz
Speed	:	1460 RPM
Poles	:	4

The switching control block for 3-level Flying capacitor inverter was shown in Fig.6. The other two inverters (2-level and 5-level) control can be implemented in a similar manner by appropriately removing/adding the carrier signal blocks.

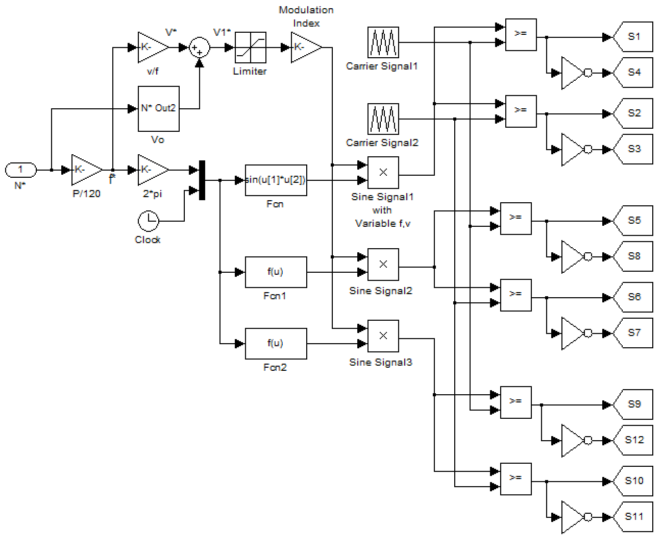


Fig.6 Switching Control Block for the 3-Level Inverter fed Induction Motor Drive

In the switching control block shown in Fig.6, from the reference speed obtained after processing the speed error through PI-controller and limiter and adding it to measured speed, the frequency was calculated and converted to radians (ω). From this the three sinusoidal modulating signals for the SPWM were obtained by multiplying 'ω' with time 't' as follows.

$$S\,\text{in}(\omega * t)$$

$$S\,\text{in}(\omega * t - \frac{2 * pi}{3})$$

$$S\,\text{in}(\omega * t + \frac{2 * pi}{3})$$

By multiplying the frequency obtained with constant v/f ratio and adding boost voltage to it, the required voltage was obtained. Then by dividing it with rated voltage, the modulating Index was obtained. Now the three sinusoidal modulating signals with variable frequency and voltage were ready for the SPWM, which is used for generating the control signals for switches of the inverter.

The simulation was carried out to evaluate both the steady state and dynamic performance of the induction motor drive. THD variation with frequency was also evaluated.

A. Dynamic Performance

The dynamic performance of 2-level PWM inverter and 3-level,5-level Flying capacitor inverters fed induction motor drive under varying conditions of load torque and speed was shown in Fig.7 (a) - Fig.7 (i).

Step Change in Load:

Motor is first started on no load with reference speed of 1500rpm. Starting torque will be developed to accelerate the machine. Once the speed reaches to reference speed torque developed also set to zero, at 0.5sec a load torque of 90N-m is applied. Sudden application of load on the rotor causes an instantaneous fall in the speed of the motor. In response to this drop in speed value, the output of the controller responds by increasing the reference speed value. So developed torque increases and motor speed settles at steady value again, and winding currents will increase. The dynamic performance characteristics under this condition are shown in Fig.7 (a)-(c).

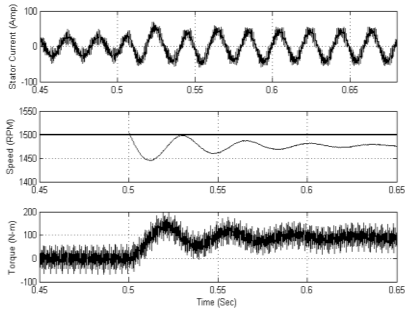


Fig.7 (a) 2-Level

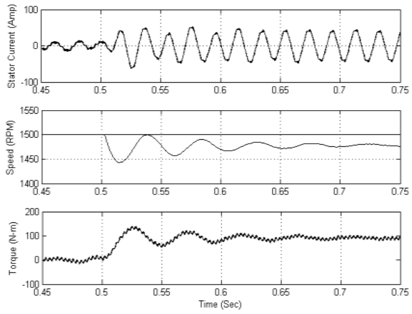


Fig.7 (b) 3-Level

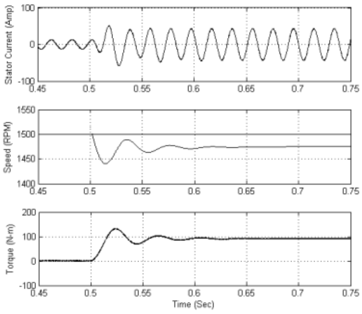


Fig.7 (c) 5-Level

Step Change in Speed:

Initially motor is started with a reference speed of 1200rpm, and motor reaches its steady-state speed and settles there. At 0.5 sec motor references speed is increased to 1500rpm, so due to controller action again motor develops torque to reach its reference value. The dynamic performance characteristics under this condition are shown in Fig.7 (d)-(f).

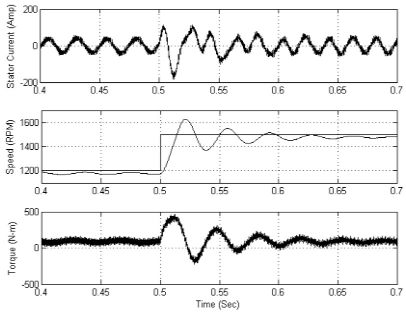


Fig.7 (d) 2-Level

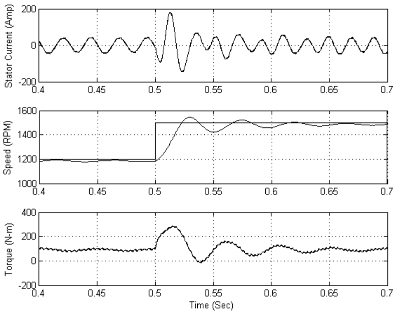


Fig.7 (e) 3-Level

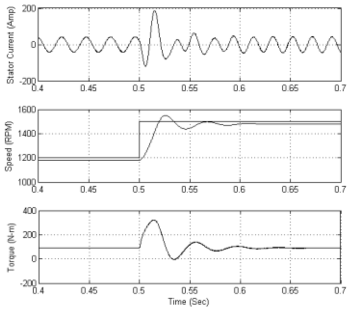


Fig.7 (f) 5-Level

Speed Reversal:

When the reference speed is changed from 1500rpm to -1500rpm, the motor tends to run in the reverse direction. When the controller observes this change, it first reduces the frequency of the stator currents followed by the phase reversal for starting the motor in the reverse direction. As the drive is in the same dynamic state (on load) just before and after the reversal of the phenomena, the steady state values of the inverter currents are observed to be the same in either directions of the rotation of the motor. However the phase sequence of these currents in two directions will be different. The dynamic performance characteristics under this condition are shown in Fig.7 (g)-(i)

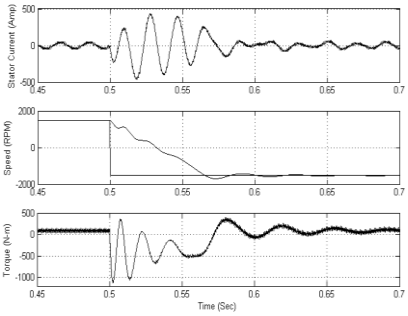


Fig.7 (g) 2-Level

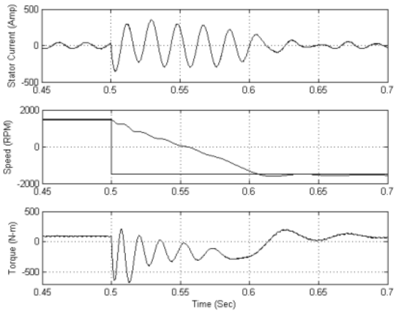


Fig.7 (h) 3-Level

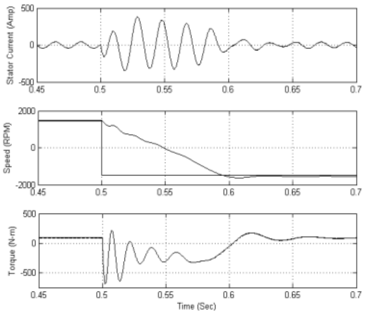


Fig.7 (i) 5-Level

Fig.7 (a)-(i) Dynamic performance Characteristics of 2-level PWM inverter and 3-Level, 5-level Flying capacitor Inverter fed Induction Motor Drive

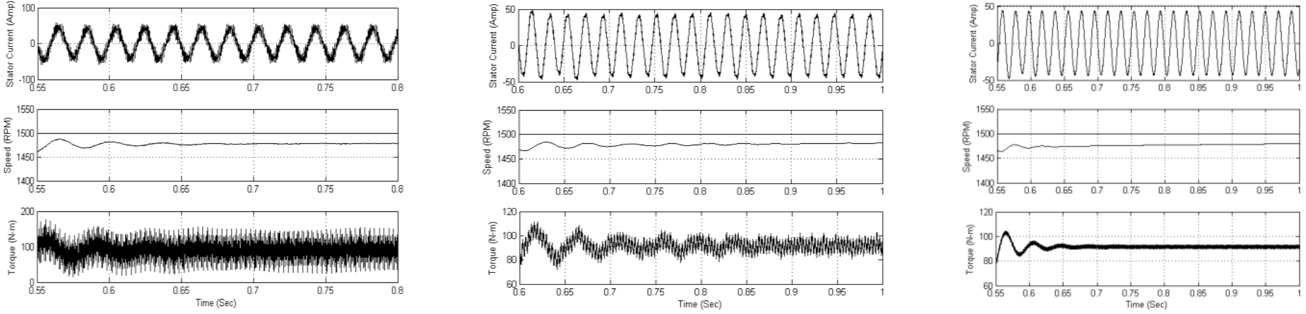
From the dynamic response characteristics, the following conclusions may be drawn regarding the performance of the drive.

1. As the level of the inverter increases, the number of ripples in the dynamic performance characteristics decreases.
2. The peak-overshoot and magnitude of ripples in the dynamic performance characteristics decreases, with the increase in level of the inverter.

B. *Steady-state Performance*

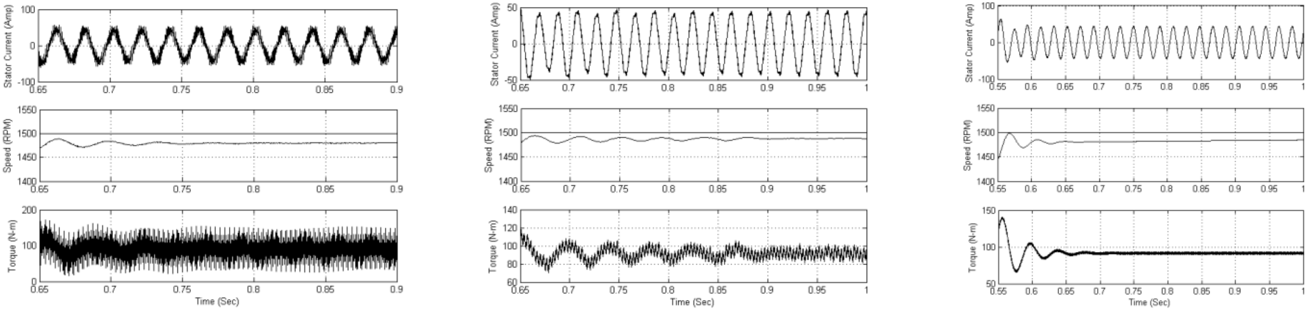
The steady-state performance of 2-level PWM inverter and 3-level,5-level Flying capacitor inverters fed induction motor drive under varying conditions of load torque and speed was shown in Fig.9 (a) - Fig.9 (i).

Step Change in Load:



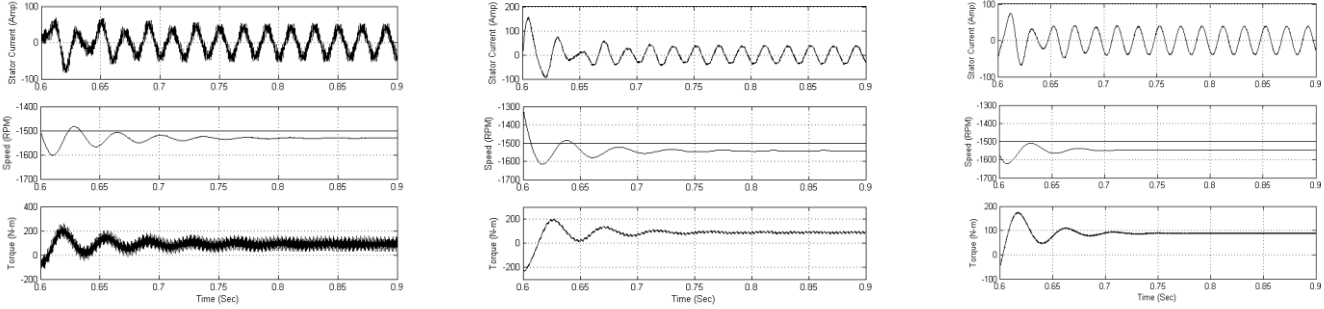
(a) 2-Level (b) 3-Level (c) 5-Level

Step Change in Speed:



(d) 2-Level (e) 3-Level (f) 5-Level

Speed Reversal:



(g) 2-Level (h) 3-Level (i) 5-Level

Fig.8 (a)-(i) Steady-state performance Characteristics of 2-level PWM inverter and 3-Level, 5-level Flying capacitor Inverter fed Induction Motor Drive

From the steady-state response characteristics, it can be observed that the time to reach steady-state response after sudden change in load torque or speed decreases with the increase in the level of the inverter.

C. *THD Variation with Frequency*

The frequency is varied over a range (20Hz - 90Hz) by keeping the load as constant. The line current THD variation with frequency for all the three inverters fed drive was comparatively shown in Fig.9 for all the inverters. It can be observed that the line current THD was decreasing with increase in frequency, because with increase in frequency the inductive reactance increases and provides filtering action for the current. The THD values of 3-level inverter were significantly less compared to 2-levl inverter. It can be also observed that the THD variation curve for 5-level is well below the curves of other two inverters.

From the figure it can be observed that there was a large decrease in current THD from the low to high frequency operation, which means the low frequency operation of the drive is going to be lossy and noisy compared to the high frequency operation, Which means that either the low frequency operation has to be avoided or some extra means of compensating or filtering the harmonics have to be employed. The improvement in the THD, from the lowest to the highest frequency is high in case of 2-level inverter and minimum in case of 5-level inverter. But the absolute value of THD is minimum for the 5-level inverter for the entire range of frequency. Therefore 5-level inverter offers better choice in reducing THD.

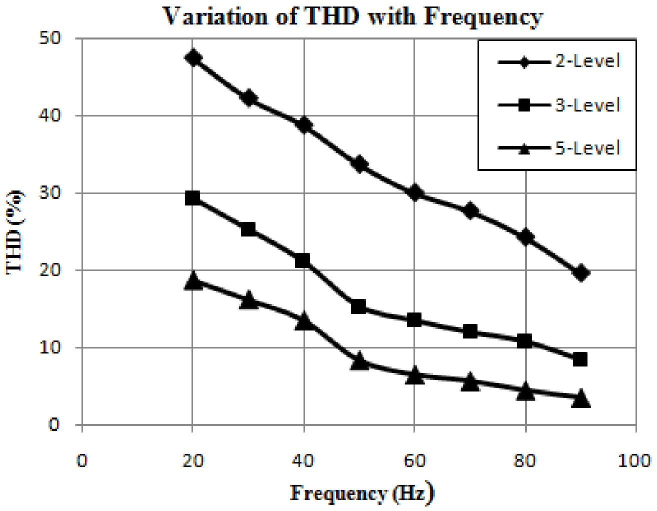


Fig.9 Comparison of Line Current THD Variation with Frequency

VI. CONCLUSION

In this paper the performance of conventional 2-level PWM inverter and 3-level, 5-level Flying capacitor inverters fed induction motor drive under varying conditions of load torque and speed was evaluated and the comparison of both the dynamic performance and steady-state performance has been presented. The line current THD variation with frequency was also comparatively presented. It was concluded that the THD and hence the performance of the drive was improved in going from 2-level to multilevel and with the increase in level of the inverter in case of multilevel inverter.

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