Cascaded H-Bridge Multilevel Inverter For Multiphase Drive Applications

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V/f Control of Five-Phase Induction Motor Drive Fed from Cascaded H Bridge Multilevel Inverter

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***Abstract*— A multilevel inverter has its own advantages over normal inverters for high voltage applications such as reduced harmonics, and better AC output. Multi-levels are realized by different techniques e.g. Flying capacitors, Neutral point clamp capacitor, Cascaded H-bridge, and Packed U-cell. In this paper, five-level voltage is modulated for five-phase induction motor drive. Multilevel inverters for multiphase drives has coalesced benefits of multilevel and multiphase, which makes the system an excellent solution for higher voltage applications. In this paper cascaded H-bridge inverter topology has been used for generating the five-level voltage output which is then fed to the five-phase drive and a volt/hertz control is applied for proper operation of the system. The machine is made to run at different load conditions and a satisfactory result is observed through simulation which ultimately verifies the suitability of the control and modulation.**

Keywords—Cascaded H bridge inverter; Multilevel, Five-Phase Induction motor, Volts/Hertz Control.

I. INTRODUCTION

Drives with the number of phases, more than three are receiving increased attention from the industry and academia due to their advantages associated with their three-phase counterpart, in high power drive applications, particularly where reliability is a key concern. In addition to enhanced reliability, multiphase drives also have significant advantages as compared to three-phase [1]-[4], which can be realized as;

- Reduction in the current ratings of power switches, as there is the possibility of splitting the power rating into more than the three phases. Therefore, they can be used for higher power applications.
- A significant improvement in the fault tolerance of the drive.
- Improved efficiency of multiphase drives due to reduced space harmonic content of the magneto-motive force.
- Torque pulsation reduction.

Due to the above advantages, multiphase drive systems can be used in many industrial applications such as high power industrial applications, locomotive traction, electric ship propulsion, etc. [1], [5]-[6], making them attractive for many Propulsion [1-3]. Moreover, Reduced per phase power significantly reduced the semiconductor components current-rating. Additionally, ‘d’ and ‘q’ current is still available for independent control of the torque and flux control and an *n*-phase machine will remain to function with a revolving field in postfault operation up to n-3 phases are faulty.

Developments in the multiphase drive area have been usually based on the utilization of two-level voltage source inverters (VSIs), with the machine’s stator winding in star connection and isolated neutral point. Various modulation techniques have been developed for various phase numbers, which take into account the nature of the multiphase system and enable the realization of desired reference voltage on average in a switching period.

Although the use of multilevel inverter supply is well-established for three-phase drives, the same does not apply to multiphase drive systems. A few viable solutions to PWM control of multilevel multiphase VSIs have been reported only very recently and this is, beyond any doubt, one research direction that will be relevant in the future as well. The increased number of levels in the output voltage decreases the harmonics causing lower acoustic noise and Electro-Magnetic Interference (EMI). The two most common multilevel inverter topologies are the diode clamped inverter and the cascaded inverter. The cascaded multilevel inverter is made up of a series of single-phase inverters, each with their own isolated DC bus [4-5]. The multilevel inverters can generate almost sinusoidal output voltage waveform from several separate DC sources. One of the advantages of this topology is the modular nature of the modulation, control and protection requirement of each bridge.

II. MODEL DESCRIPTION & CONTROL ALGORITHM

The model consists of the following building blocks:

a) Five Phase Multi-Level Inverter
b) Volts/Hertz Algorithm for control of an Induction motor drive.

Control Algorithm reads the speed of the induction motor and compares it with the reference signal. The error generated is processed by a PI Controller to give the required slip speed. This slip speed is processed to give voltage and frequency required for tracking the desired speed. The variation of voltage and frequency is such that Volt/Hertz remains constant. The complete system is as shown in Fig 1.

A. *Five Phase Multi-Level Inverter*

Fig 2 shows the implementation of single-phase H-Bridge cells. There is two H-bridge cells for each phase. Each cell consists of four switches and a dc source as shown. Different switching combinations determine different voltages such as V+, V- and 0. The number of levels in multilevel inverter depends upon the number of separate DC sources. That follows the relation is $m=2s+1$, where m is no. of voltage level and 's' is no. of separate DC sources. The output from the H-Bridges is quarter symmetry to generate a sine wave. Due to quarter-wave symmetry, even harmonics will be absent. As there are separate DC sources, that make freedom of selection of source, either from sunlight, wind or any other natural resources. Moreover, it does not require any capacitor or diodes for clamping. And due to multilevel, the output has low THD.

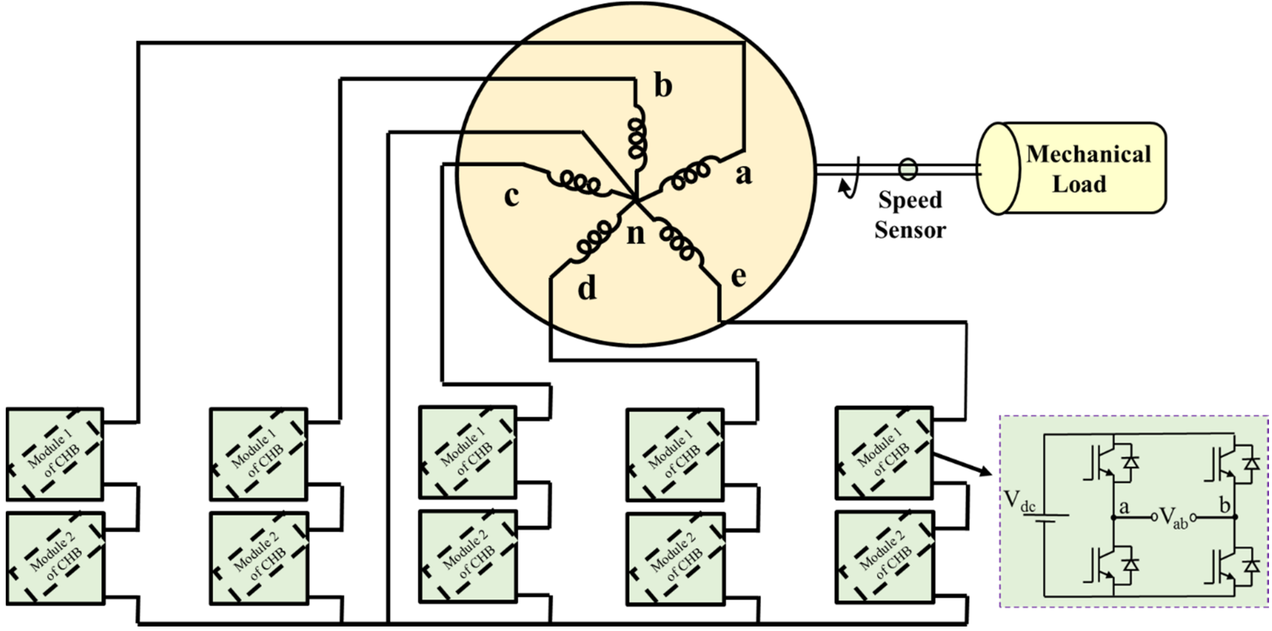

Fig. 1 Five-Phase Induction Motor Drive fed by five phases of five-level inverters.

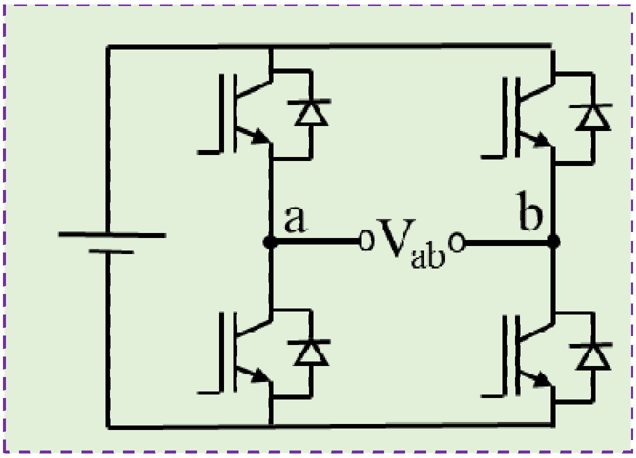

Fig. 2 H-Bridge Cell consisting of dc source and four switches.

B. *Sinusoidal Pulse Width Modulation (SPWM)*

Conventional Sine PWM is used for generation of switching pulses by comparing the modulating signal with a carrier signal

Where the variable controlled output voltage can be obtained by controlling the amplitude modulation index. The variable-frequency can be obtained by changing the frequency of the reference signal of the output voltage. Fig 4(c) displays the reference and carrier signals for pulse generation. In the switching bipolar scheme is applied, in this scheme, the two legs of the full-bridge inverter switches are triggered simultaneously. Using V_{ref}, five 72° degrees displaced modulating signals are generated.

This sine PWM is largely used in industrial applications due to simple control. The ratio of carrier and modulating signal frequency defines the pulses in a switching period. The modulating signal controls the inverter output frequency f_o and the amplitude modulation index m_a controls the amplitude of the output voltage. The frequency modulation index and amplitude modulation index is defined by the equation (1) and (2).

$$m_f = \frac{f_{car}}{f_c} \tag{1}$$

$$m_a = \frac{V_c}{V_{car}} \quad (2)$$

Where,

f_{car} = Carrier signal frequency (triangular signal),
f_c = Control signal frequency (sine signal),
V_{car} = Amplitude of carrier signal,
f_c = Amplitude of reference signal.

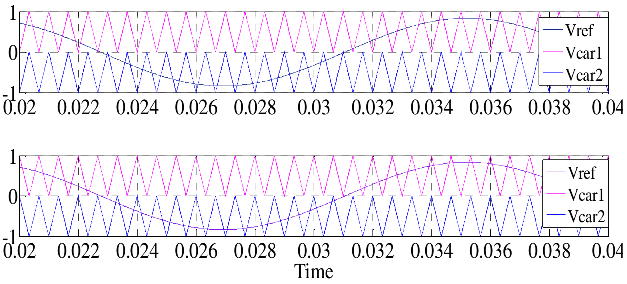

Fig. 3 Carrier and modulation signal comparison for pulse generation for four switches.

For the generation of five-level output voltage, two H-bridges are connected in cascade to form one phase of the inverter. For the five-level five-phase inverter, there should be 10 such H-cells. The cascaded H-bridge cells for Phase A are given the same reference signal, the only difference being that the carrier signal is phase-shifted by 90° following 180°/n where n is the no. of cells in each phase [6-7]. The modulation signal for the phases should be generated such that they are displaced from each other by 72°.

C. *Volts/Hertz Control Algorithm*

The induced emf in a phase winding is proportional to the rate of change of flux in the winding. From this, it is obtained that the maximum flux is proportional to the induced voltage and inversely proportional to the frequency of the stator voltage. Since machine design is done in such a way to give maximum efficiency i.e. maximum flux. But for speed control, if one changes the frequency, then ϕ_m has also changed correspondingly. To operate the motor at constant flux volts /Hertz ratio remains constant. For that, voltage is also controlled from controlling the reference signal modulation in inverter [8-10]. The mathematical relationship for the above discussion is as given below.

$$E_{as} = -\frac{d\lambda}{dt} \quad (3)$$

$$E_{as} \; \alpha \; k_w \phi_m f_s \quad (4)$$

$$\emptyset_m \; \alpha \; \frac{E_{as}}{f_s} \quad (5)$$

For the control of the drives speed, generally, rotor resistance or stator voltage control can help. However, the efficiency of the drives suffers at lower speed especially. Literature shows that the efficient way of the control of the drive is the variation of the supply frequency. This helps to control the speed in a wide range and moreover improves the starting characteristics of the drive as compared to the resistance and input voltage control. Moreover, a wide range of speed control is can be achieved. The very important point in frequency control is that, if the drive is operating below rated speed then

the ratio of the voltage and frequency should remain fixed to keep the flux constant. Keeping the flux constant helps to maintain the torque capability of the drive the same. However, at very low frequency there are some shortcomings which include the reduction of torque capacity. This reduced capacity should be compensated by increasing the applied voltage.

The control Algorithm senses the motor speed and compares it with the actual speed. The error generated is processed to generate the required synchronous speed for tracking the required speed. This speed is converted into frequency. For maintaining constant Volt/Hertz control, the required voltage is obtained from the synchronous speed. Now the obtained values of frequency and voltage are used for determining the reference/modulating signals for the five-phase inverter. These modulating signals are then compared with the respective carrier signals of each phase to generate firing pulses for H-Bridge Cells. The control algorithm is as shown in Fig 4.

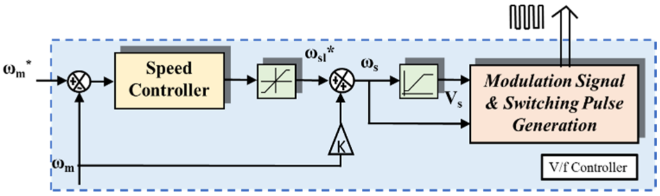

Fig. 4 Control Algorithm of Induction Motor Drive

III. SIMULATION RESULTS

The steady-state performance of the machine drive is validated through simulation results. The modeled system is tested by applying the reference speed and noting down the behavior. Fig 5 shows the steady-state speed and torque response of the drive under no-load condition. Moreover, the system is immune against any variation in load owing to its well-designed closed-loop control. Initially, the model is given a reference speed of 850 rpm which the machine attains steadily after the settling period is over. The disturbance on the motor is realized by varying load torque in stepped form. The machine performs satisfactorily during load variation and speed control is successfully achieved.

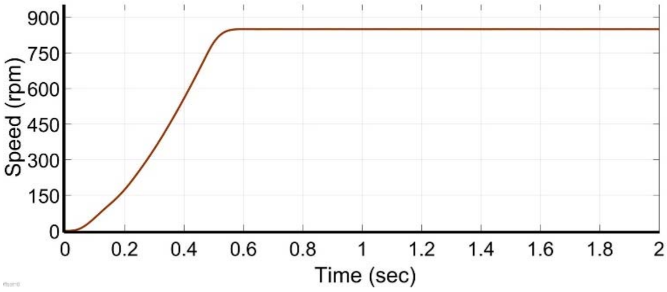

Fig.5 Motor running at speed 850 rpm at no load

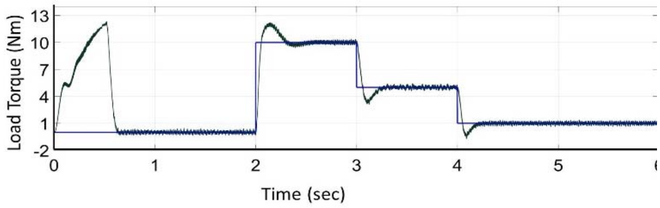

Fig. 6 Variation in load torque as mentioned below

The speed references and the load torque on the machine are applied in the following sequence and the system performance can be observed from fig. 6.

a. At *t = 0* sec, the speed reference is 850rpm.
b. At *t = 2* sec, the load torque of 10Nm is applied.
c. At *t = 3* sec, the load torque is reduced from 10Nm to 5Nm.
d. And At *t = 4* sec, there is a change in load torque from 5Nm to 2Nm.

TABLE I. MOTOR PARAMETERS

Parameters	**Power (kW)**	**Voltage (V)**	**Pole pairs**	**Speed (rpm)**	**Rotor resistance (Ω)**	**Stator resistance (Ω)**	**Stator Inductance (mH)**	**Rotor Inductance (mH)**	**Inertia (kg.m^2)**
Specifications	3	230	3	850	15.5	25.3	103.1	92.2	0.021

Fig 7 shows the speed and torque response of the system for given speed references and load torque demands.

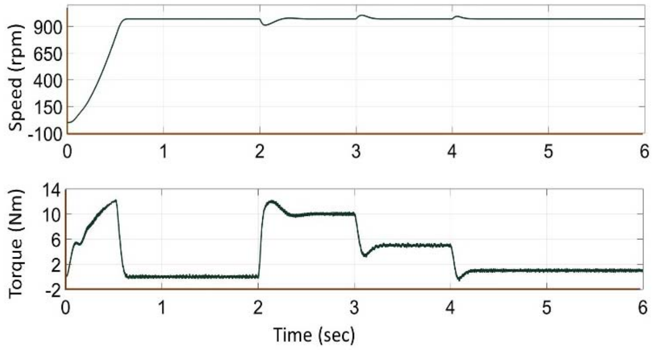

Fig. 7 Speed and torque response of the controlled system

At starting, the machine steadily rises to approach the required steady-state speed. Once the motor reaches its steady-state speed, the torque developed by the motor is reduced as there is no more requirement of acceleration of the motor. The modulating signal shown in Fig 8, varies accordingly to keep the ratio Volt/Hertz constant. It can be observed that the frequency of the modulating signal is low at the starting with corresponding magnitude keeping V/f constant.

At t = 2 sec, the load torque demand is increased to 10Nm. For a drive operating in a stable region, there should be a decrease in speed when load torque is applied to the system. This behavior can be clearly observed in the response shown. After the speed dips momentarily, the control algorithm comes into play to restore the speed back to the reference value.

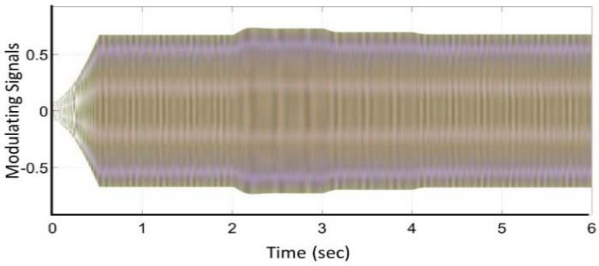

Fig.8 Variation of modulation signal magnitude and frequency during Volt/Hertz control.

At t = 4 sec, the load torque demand is decreased to 5Nm. For stable region operation, the speed should rise when there is a sudden decrease in load torque. The speed increases momentarily and then the control algorithm brings it back to the desired speed. Fig 9 shows the output voltage of phase A of the five-phase inverter. Since the appropriate switching technique is implemented, the multi-level output is obtained. The phase difference between the two phases is also maintained at 72º by the control algorithm. This can be clearly observed by the modulating signal waveform shown in Fig 10.

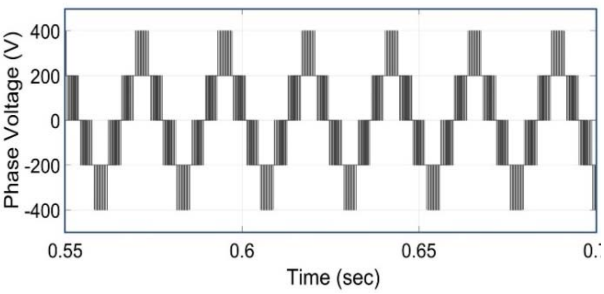

Fig. 9 5 Level Output Voltage of five-phase Inverter

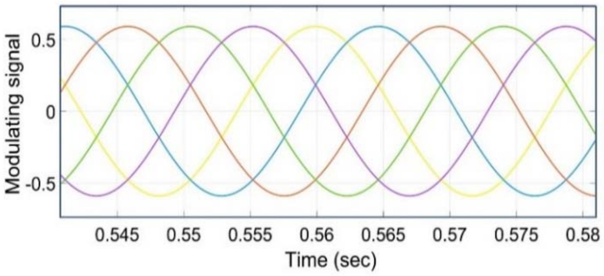

Fig. 10 Modulating signal for five-phase inverter generated by the control algorithm.

IV. CONCLUSION

The paper discusses multilevel inverter fed five-phase Induction Motor drive controlled by a closed-loop Volt/Hertz Algorithm. A brief review of the operating principle is provided. The main focus is on the analysis of speed control in different load changing conditions. The transient for the drive is analyzed that confirms the speed control of the closed-loop drive during conditions of load change as well as transients. The response of the drive also validates its operation in the stable operating region. Five phase inverter is successfully implemented using a Multi-Level Inverter.

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