Modelling, Simulation and Performance Analysis of A Variable Frequency Drive in Speed Control Of Induction Motor

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Abstract: *The need for variable speed of an ac induction motor arises in certain industrial applications and this is often difficult to achieve because induction motors are of fixed speed. The available control techniques such as variation of supply voltage, variation of number of poles, are characterized by low efficiency and high maintenance cost. The improvement in power electronics technology through advancements in semi-conductor electronic devices with increased reliability and reduced cost led to the development of modern solid-state variable frequency motor drive which is an electronic device capable of controlling the speed of an induction motor by varying the frequency with increased efficiency, reliability and low maintenance cost. This paper carried out the modelling, simulation and performance analysis of such a variable frequency drive using matlab /simulink model. It successfully achieved the control of the speed of the induction motor from zero to the nominal speed by varying the frequency of the applied ac voltage using pulse width modulation method.*
Keywords: *Induction Motor, Inverter, matlab/simulink model, Pulse Width Modulation, Variable Frequency Drives.*

I. Introduction

Induction motors are fixed speed motors which are used in most industries because of its reduced cost, reliability and rugged nature. In industrial applications which require variable speed, the use of induction motor is limited as a result of low efficiency and high cost penalty associated with the existing control techniques.

The improvement and advancement in power electronics has led to the production of ac motor drives known as a variable frequency drive (VFD), which are now used to control the speed of induction motors at reduced production and maintenance cost with increased efficiency.

A variable-frequency drive (VFD) is a system for controlling the rotational speed or torque of an alternating current (AC) electric motor by controlling the frequency of the electric power supplied to the motor [1].

A variable frequency drive is a type of adjustable speed drive also referred to as AC drives, adjustable frequency drives, frequency converters, micro drive or inverter drives. It controls the speed of the electric machine by converting the frequency of the grid to adjustable values on the machine side, thus allowing the electric motor to quickly and easily adjust its speed to the required value. The two major functions of a variable frequency drive are to provide power conversion from one frequency to another, and to enable control of the output frequency. Variable-frequency drives are used in applications ranging from small appliances to the largest of mine mill drives and compressors. They are also widely used in ventilation systems for large buildings, variable frequency motors on fans which save energy by allowing the volume of air moved to match the system demand. They are also used on pumps, conveyors and machine tools drives. Variable frequency drives can be classified as;

- AC variable frequency drives
- Current source input variable frequency drives
- Pulse width modulated variable frequency drives
- Flux vector pulse width variable frequency drives.

II. Variable frequency drive operation

The basic principle behind VFD operation requires an understanding of the three basic sections: the Rectifier unit, DC Bus and the Inverter unit, as shown in figure 1 [2].

The supply voltage is first passed through a Rectifier unit where it gets converted from AC to DC supply; the three phase supply is fed with three phase full wave diode where it gets converted into DC supply. The DC bus comprises a filter section where the harmonics generated during the AC to DC conversion are filtered out. The last section consists of an inverter section which comprises six Insulated Gate Bipolar Transistors (IGBT) where the filtered DC supply is being converted into quasi-sinusoidal wave of AC supply which is supplied to the induction motor connected to it [3]. It is known that the synchronous speed of an electric motor is dependent on the frequency. Therefore by varying the frequency of the power supply through VFD the speed of the motor can be controlled

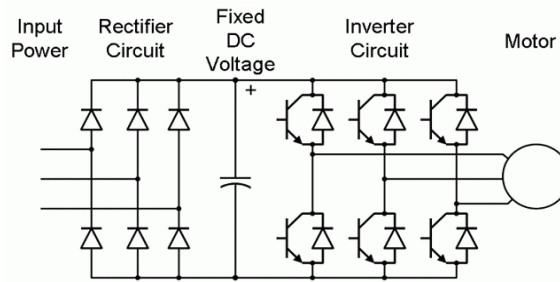Speed (rpm) $n_r = \dfrac{120f}{P}$ (1)

Fig. 1: VFD circuit Diagram

where; f = Electrical Frequency of the power supply in Hz, p = Number of electrical poles in the motor stator [4]. The variation in frequency and corresponding speed are shown in Table 1 and represented in Figure 2 below.

Table 1 Frequency variation and corresponding rotor Speed

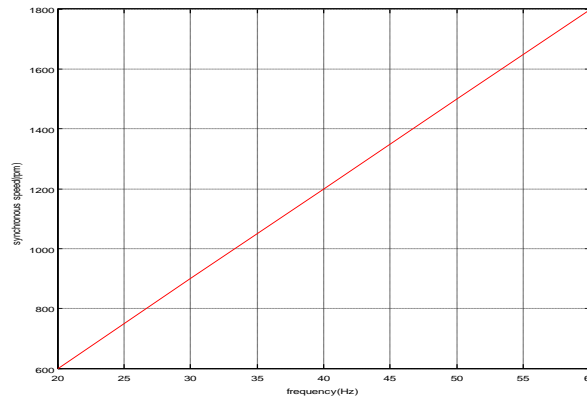| Frequency (f), Hz	Speed (n), rpm
20	600
25	750
30	900
35	1050
40	1200
45	1350
50	1500
55	1650
60	1800

Fig. 2: Graph of rotor speed versus frequency

Thus, we can conveniently adjust the speed of a motor by changing the frequency applied to the motor and keeping the number of poles constant. There is another way to change the speed of the motor by changing the no. of poles, but this change would be a physical change to the motor. As the drive provides the frequency and voltage of output necessary to change the speed of a motor, this is done through Pulse Width Modulation Drives. Pulse width modulation (PWM) inverter produces pulses of varying widths which are combined to build the required waveform.

As the frequency is variable as compared with the poles of the motor therefore speed control drive is termed as Variable Frequency Drive (VFD) [5].

III. Constant V/F Ratio Operation

All Variable Frequency Drives maintain the output voltage – to – frequency (V/f) ratio constant at all speeds for the reason that follows. The phase voltage V, frequency f and the magnetic flux Φ of the motor are related by the equation: V = 4.444 f NΦ$_m$

Or V/f = 4.444NΦ$_m$

where N = number of stator turns per phase.

Φ$_m$ = magnetic flux

If the same voltage is applied at the reduced frequency, the magnetic flux would increase and saturate the magnetic core, significantly distorting the motor performance. The magnetic saturation can be avoided by keeping the Φ$_m$ constant. Moreover, the motor torque is the product of stator flux and rotor current. For maintaining the rated torque at all speeds the constant flux must be maintained at its rated value, which is basically done by keeping the voltage – to – frequency (V/f) ratio constant. That requires the lowering of the motor voltage in the same proportion as the frequency to avoid magnetic saturation due to high flux or lower than the rated torque due to low flux.

IV. 4.0 How Drive Changes Motor Speed

As the drive provides the frequency and voltage of output necessary to change the speed of a motor, this is done through Pulse Width Modulation Drives. Pulse width modulation (PWM) inverter produces pulses of varying widths which are combined to build the required waveform.[6] as shown in Fig. 2. A diode bridge is used in some converters to reduce harmonics. PWM produces a current waveform that more closely matches the line source, which reduces undesired heating. PWM drive has almost constant power factor at all speeds which is close to unity. PWM units can also operate multiple motor on a single drive [6].

Thus the carrier frequency is derived from the speed of the power device switch remains ON and OFF drive. It is also called switch frequency. The higher the carrier frequency of the power line the higher the resolution of the pulse width modulation. The typical carrier frequency ranges from 3 to 4 KHz or 3000 to 4000 cycles per second as compared with older SCR based carrier frequency which ranges from 250 to 500 cycles per second [7]. Thus it is clear that the higher the carrier frequency the higher

will be the resolution of output waveform.

It is also noted that the carrier frequency decreases the efficiency of the drive because it leads to increased heat generation of the drive circuit.
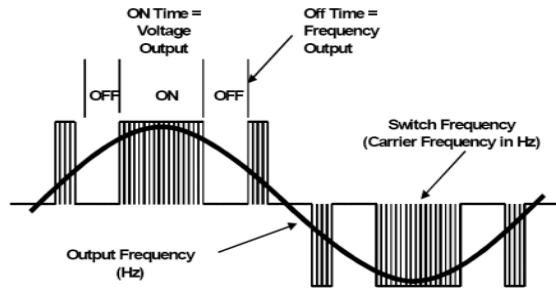

Fig. 3: Drive Output Waveform of Pulse Width Modulator

V. Mathematical modelling of a three phase voltage source

The three phase voltage source is the provider of AC three phase voltages with constant frequency of ω_e which puts LC filtered three phase voltages on induction motor stator and is modelled using (2) to (4);

$$V_{as} = V_m \cos w_e t \qquad (2)$$

$$V_{bs} = V_m \cos(w_e t + \theta) \qquad (3)$$
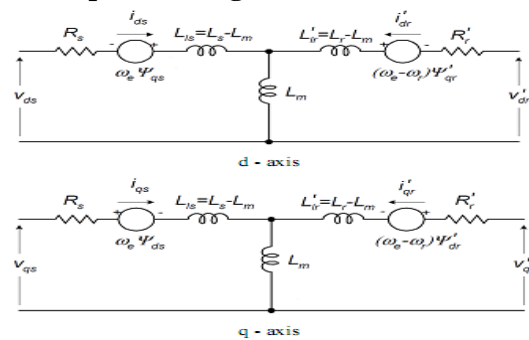
$$V_{cs} = V_m \cos(w_e t - \theta) \qquad (4)$$

Fig. 4: Equivalent dqo circuit diagram of an induction motor

VI. Model of the induction motor

The three phase induction motor works as a converter of electrical energy to mechanical energy that exerts the electromagnetic torque to the load. The induction motor is modeled using transformation of fixed abc coordinates to rotating dqo coordinates. The equivalent circuit diagram of dqo coordination is shown in Fig.4. The three phase induction motor model maybe formulated as mentioned in the equations below [5]. From the above diagram the following equations are obtained for the flux;

$$\varphi_{qs} = L_s i_{qs} + L_m i'_{qr} \qquad (5)$$

$$\varphi_{ds} = L_s i_{ds} + L_m i'_{dr} \qquad (6)$$

$$\varphi'_{qr} = L'_r i'_{qr} + L_m i_{qs} \qquad (7)$$

$$\varphi'_{dr} = L'_r i'_{dr} + L_m i_{ds} \qquad (8)$$

$$\text{where } L_s = L_{is} + L_m \qquad (9)$$

$$L'_r = L'_{ir} + L_m \qquad (10)$$

For the stator side

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_e \varphi_{ds} \qquad (11)$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_e \varphi_{qs} \qquad (12)$$

For the rotor side

$$V'_{qr} = R'_r i'_{qr} + \frac{d}{dt}\varphi'_{qr} + (\omega_e - \omega_r)\varphi'_{dr} \qquad (13)$$

$$V'_{dr} = R'_r i'_{dr} + \frac{d}{dt}\varphi'_{dr} - (\omega_e - \omega_r)\varphi'_{qr} \qquad (14)$$

At this investigation, $V_{qr}^{'}$ and $V_{dr}^{'}$ are set to zero for a squirrel cage induction machine.

The generated electromagnetic torque is given as

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right) L_m (i_{dr} i_{qs} - i_{qr} i_{ds}) \tag{15}$$

Where,

L_m is the mutual inductance

L_{is} is the stator leakage inductance

L_{ir} is the rotor leakage inductance

I_{qs} is the Q-axis component of the stator current

I_{ds} is the D-axis component of the stator current

I_{qr} is the Q-axis component of the rotor current

I_{dr} is the D-axis component of the rotor current

φ_{qs} is the Q-axis component of the stator flux

φ_{ds} is the D-axis component of the stator flux

φ_{qr} is the Q-axis component of the rotor flux

φ_{dr} is the D-axis component of the rotor flux

V_{qs} is the Q-axis component of the stator voltage

V_{ds} is the D-axis component of the stator voltage

V_{qr} is the Q-axis component of the rotor voltage

V_{dr} is the D-axis component of the rotor voltage

ω_e is the rotating velocity of the applied two-phase Q-D reference frame

ω_r is the rotating velocity of the motor rotor in electrical degrees

R_s is the stator resistance

R_r is the rotor resistance

VII. Effect of change in supply voltage on starting torque

If $T_{st} = \frac{K_1 E_2^2 . R_2}{(R_2^2 + X_2^2)}$ (16)

Substituting $E_2 = $ supply voltage V

Then, $T_{st} = \frac{K_1 V^2 R_2}{(R_2^2 + X_2^2)} = \frac{K_1 V^2 . R_2}{Z_2^2}$ (17)

Substituting, $K_3 = \frac{K_1 R_2}{Z_2^2}$, then

$T_{st} = k_3 V^2$ (18)

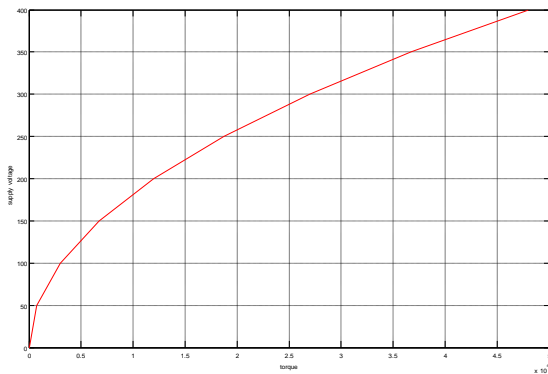The graph in Figure 5 below represents the relationship between torque and supply voltage.
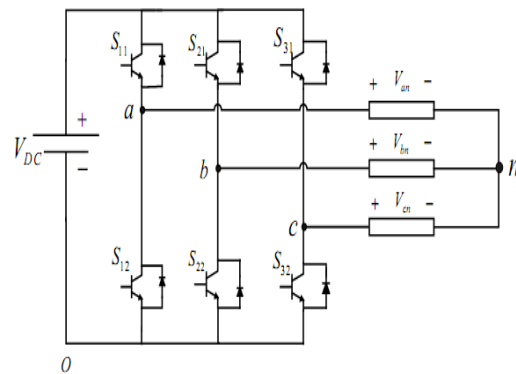

Fig. 5: Graph of supply voltage versus torque

Fig. 6: Three-phase Full–Bridge Inverter

VIII. Inverter model

The inverter model shown in Figure 6 has eight switch states given in Table 2. In order that the circuit satisfies the KVL and the KCL, both of the switches in the same leg cannot be turned ON at the same time, as it would short the input voltage violating the KVL. Thus, the nature of the two switches in the same leg is complementary

$S_{11} + S_{12}$ (19)

$S_{21} + S_{22}$ (20)

$S_{31} + S_{32}$ (21)

Table 2: The switching states three-phase inverter

S_{11}	S_{12}	S_{31}	V_{ab}	V_{bc}	V_{ca}
0	0	0	0	0	0
0	0	1	0	$-V_{DC}$	V_{DC}
0	1	0	$-V_{DC}$	V_{DC}	0
0	1	1	$-V_{DC}$	0	$-V_{DC}$
1	0	0	$-V_{DC}$	0	$-V_{DC}$
1	0	1	$-V_{DC}$	$-V_{DC}$	0
1	1	0	0	V_{DC}	$-V_{DC}$
1	1	1	0	0	0

The selection of the states in order to generate the given waveform **in a** done by the modulating technique that ensures the use of only the is valid states.

$$\frac{V_{DC}}{2}(S_{11} - S_{12}) = V_{an} + V_{no} \qquad (22)$$

$$\frac{V_{DC}}{2}(S_{21} - S_{22}) = V_{bn} + V_{no} \qquad (23)$$

$$\frac{V_{DC}}{2}(S_{31} - S_{32}) = V_{cn} + V_{no} \qquad (24)$$

Expressing (22) to (24) in terms of modulation signals and making use of conditions from (17) to (19) gives:

$$\frac{V_{DC}}{2}(M_{11}) = V_{an} + V_{no} \qquad (25)$$

$$\frac{V_{DC}}{2}(M_{21}) = V_{bn} + V_{no} \qquad (26)$$

$$\frac{V_{DC}}{2}(M_{31}) = V_{cn} + V_{no} \qquad (27)$$

Adding Equations (25) to (27) to gives Equation (28);

$$\frac{V_{DC}}{2}(S_{11} + S_{21} + S_{31} - S_{12} - S_{22} - S_{32}) = V_{an} + V_{bn} + V_{cn} + V_{no} \qquad (28)$$

As we are dealing with balanced voltages,

$V_{an} + V_{bn} + V_{cn} = 0$, equation (28) becomes $\frac{V_{DC}}{6}(2S_{11} + 2S_{21} + 2S_{31} - 3) = V_{no}$ $\qquad$ (29)

Substituting for V_{no} in Equations (22) to (24) gives:

$$\frac{V_{DC}}{3}(2S_{11} - S_{21} - S_{31}) = V_{an} \qquad (30)$$

$$\frac{V_{DC}}{3}(2S_{21} - S_{21} - S_{31}) = V_{bn} \qquad (31)$$

$$\frac{V_{DC}}{3}(2S_{31} - S_{21} - S_{11}) = V_{cn} \qquad (32)$$

IX. Complete model of the speed control of an induction motor using inverter

The Simulation is done with an inverter using Pulse Width Modulation technique. Frequency and amplitude of output voltage is varied by using PWM technique and these controlled voltage and frequency are used to control motor speed. The simulink model shown in figure 7 below has the following parameters as given in Table 3.
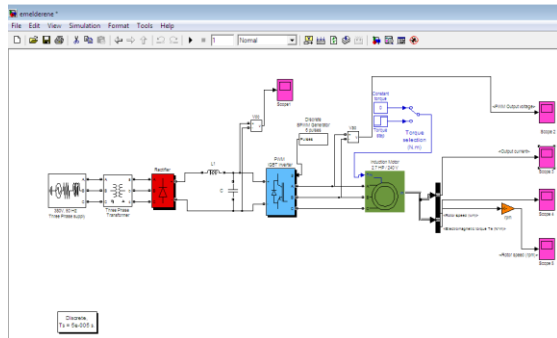

Fig. 7: SIMULINK model of speed control of an induction motor using VFD

Table 3: Simulation parameters

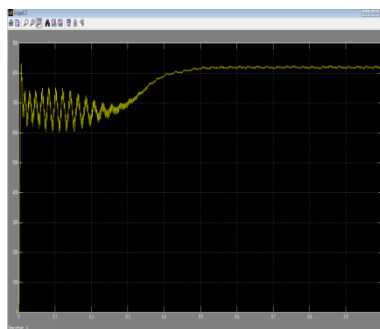| Parameter	Value
Supply Voltage	380volts (line)
Supply Frequency	50Hz
Rotor Type	Squirrel Cage
Motor Rating	2kW (2.7hp)
Number of poles	4
Normal speed	1500rpm

X. Simulation results

Fig.8: Sinusoidal AC supply voltage
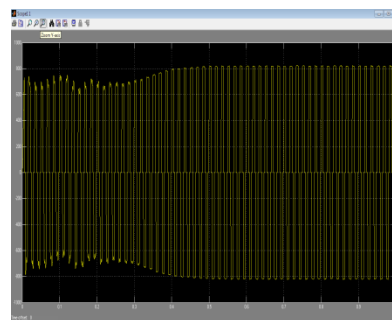

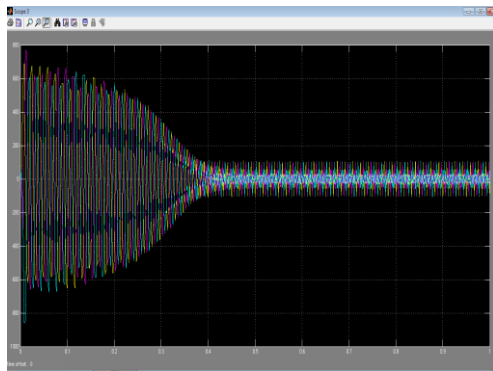**Fig.9: PMW voltage output waveform**
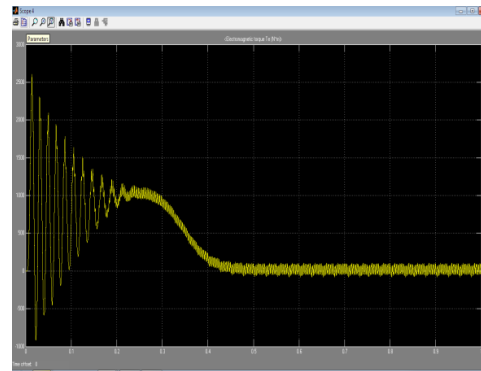
Fig. 10: Output Current waveform

Fig. 11:   Electromagnetic Torque

Figure 9, shows the three phase modulating SVPWM waveforms for the inverter. The increasing frequency of the modulating signals is clearly seen. Figure 10, shows the stator current. The parameters are initially ramping in nature till they got settled at the peakvalue at 50Hz. Figure 12, shows the Rotor speed. It is seen that the VFD has succeeded in increasing the nominal speed of the motor from using the nominal frequency of 50Hz. Initially the speed of the motor rises from zero and increases above the nominal speed; it experiences some transients and then settles to a stable level within few milliseconds. Finally figure 11 shows the electromagnetic torque of the model. VFD provides the following advantages:
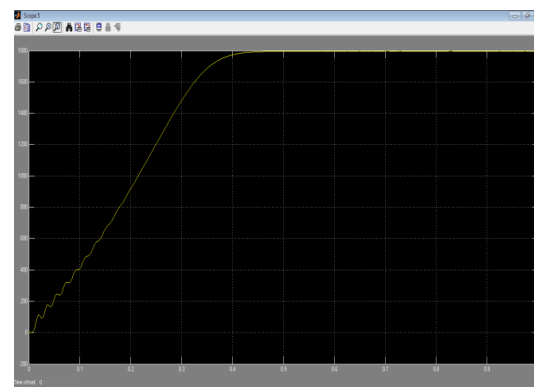

Fig. 12: Rotor Speed (rpm)

- Energy saving
- Low motor starting current
- Reduction of thermal and mechanical stresses on motors and belts during starts.
- Easy to install
- High power factor

XI.   Conclusion

Changing the electrical frequency of the supply voltage using the VFD will change the rotor speed of the motor. Changing the electrical frequency will also require an adjustment to the terminal voltage in order to maintain the amount of flux level in the motor core else the motor will experience core saturation and excessive magnetization current. Thus after the study of Variable Frequency Drive, it becomes possible to control the speed of electric motor as well as to conserve the electrical energy, as it is known that energy conservation has become an important subject all over the world. Increase in efficient energy use, decrease in energy consumption from conventional energy sources has increased which leads to conservation of energy.

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