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Devendra Pal Singh et al. 2016, Volume 4 Issue 2
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

Design, Modeling Analysis and Performance Evaluation of a Single Phase Variable Frequency Drive for Induction Motor: An Energy Conservation Approach

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Abstract

For variable load on electric motors, one of the effective methods to save energy is "Variable Frequency Drive" (VFD). It would help in conserving the energy by optimizing the energy consumption with load. In this paper the single phase variable frequency drive (VFD) is presented. The single phase VFD is used to drive the single phase motors at different frequencies. The design of single phase VFD consists of an AC to DC converter and a DC to AC converter. The VFD is designed for 150 W loads. Two steps of conversion are shown with its design parameter. The change in the output frequency and voltage is achieved with the help of synchronizing the switches with its switching frequency. However, the paper also validates the performance of single phase VFD with the simulation as well as the hardware result. The results obtained from both results show that the difference between the desired and actual result is very low and the circuit is performing accurately. The simulation is carried out on simulink of MATLAB software. The performance evaluation of the developed hardware is conducted on an electric motor of 150 W. It was found that by reducing the frequency from 50Hz to 40Hz the power consumption is reduced by 27%.

Introduction

Today in the developing world the amount of energy consumption in the form of electrical energy has increased by exponential rate. As the electrical energy not the direct form of energy, and hence it is converted from both renewable and non-renewable sources. The other method to meet the demand is the energy conservation i.e. reducing the energy wastage by the user during the use of energy. Major electrical load in industries comes through induction motors, which is responsible more than 60 – 70% load. Due to variable production, the load on motors is also variable and the efficiency of the motor get effected.

One of the effective methods to save energy in induction motor by utilising only needful energy for the performance of motor is "Variable Frequency Drive" (VFD). VFD is known as different names. Sometime it is called as adjustable-frequency drive, variable-speed drive also termed as AC drive, and also as inverter drive. [1-7]

Variable Frequency Drive

VFD is generally a power conversion device which is used to convert the fixed AC voltage and its frequency supplied from the incoming power to a variable voltage at variable frequency output as required as per the load.

Today Variable frequency drives (VFD's) are gaining a lot of attention and become the useful tool for energy conservation. Before the VFD were taken in use the change in the speed of motors were done by the use of mechanical devices such as pulleys. But in the controlling of speed by VFD mechanical pulleys are absent and thus it reduces the number of mechanical components associated in the control mechanism and due to this the overall maintenance cost is reduced. The above advantages are the secondary advantage of VFD. The primary advantage of a VFD is having the ability to save the consumer pocket money through its working method topology to save energy by consuming only the useful power from the source that is needed. [8-17]

The application of VFD varies from small electrical appliances to the large load such as mine mill drives and the compressors used in various industries.

Single Phase VSI VFD with PWM Output

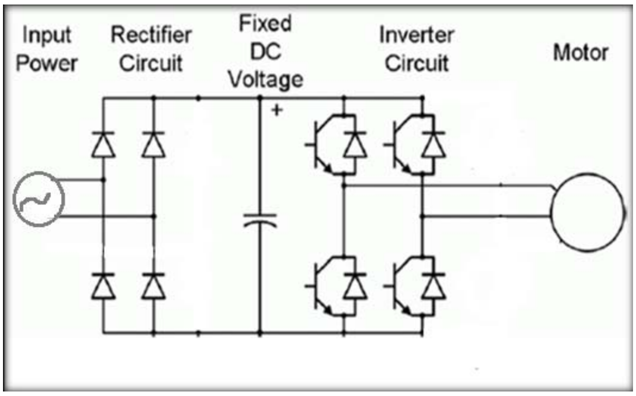

Figure 1: General Single phase VSI VFD

The figure-1 shows the configuration of a single phase VFD with the Voltage Source Inverter (VSI) single phase inverter topology. As the use of VFD, is to provide variable frequency and variable voltage at the output. In this configuration a single phase full bridge rectifier circuit is used to rectify the AC into DC voltage. A capacitor bank is used to store the voltage coming from the rectifier circuit. Capacitor also reduces the ripple across the output voltage of the rectifier circuit. Single phase voltage source inverter is used to generate single phase two pulse output power. DC voltage is applied to the inverter circuit. The switches connected in the inverter are basically thyristor or transistor. The switching pulse is given by the Pulse Width Modulation (PWM) pulse generator. A block diagram of a VFD is shown in figure-2.

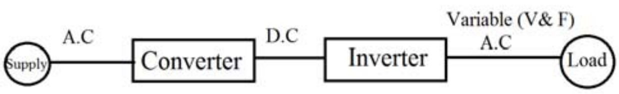

Figure 2: Block Diagram of VFD

The objectives of the present project are

(i) To simulate VFD for a load for 150 Watt at MATLAB

(ii) To develop the required hardware of the VFD

(iii) To evaluate the performance of the developed hardware for variable frequency

Simulation Software

In this work module the simulation of proposed circuit topology is done through the MATLAB^{TM} of version R2009b.

There are various advantages of using this software to simulate the model. Not only the accuracy but also various helping tools provided in this software make the simulation easy to understand and operate. The percentage of error in using this software is almost negligible. With the help of this software various experiments with a large range of variation in both input and load can be carried out which further helps to conclude the better results.

Simulation of Single Phase VFD with Filter

Using the MATLAB, a VFD for 150 W load is designed and shown in figure-3.

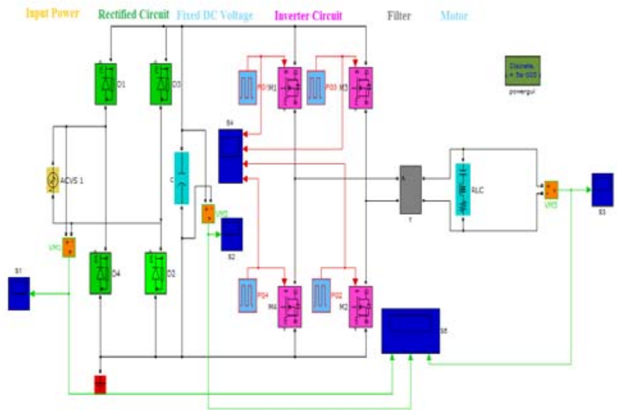

Figure 3: Designed Single Phase VSI VFD using filter simulated circuit topology

The circuit consists of a single phase rectifier circuit and the inverter circuit. In this circuit the pulse generator is denoted by “PG” and the diode are with their numbers. The filter circuit is at the output terminal of the circuit. The supply AC source is a voltage source hence termed as ACVS1. The voltage measurement is denoted by VM while the load is termed as load. Scope 5 (S5) gives the output characteristic of the topology.

The parameter used to the circuit topology is tabulated in the table-1.

Table 1: Components and their parameters to simulate the designed circuit

PARAMETER	SYMBOL	SPECIFICATION
Input Voltage	AC	220V
Switching Frequency	f_s	40, 50, 60 Hz
Output Capacitor	C_{out}	470 mF
Main Switches	M_1 to M_4	IRF840
Power Diode	D_1 to D_4	HFA08TB60

Switching Pulse to the circuit

The switching pulses are the main source to achieve variable frequency in the output. By changing the switching frequency we can change frequency across the output.

Changing the frequency is done by following methods:

(a) By changing the total time period
(b) By changing the turn on period
(c) By changing the turn off period

The switching frequency is inversely proportional to the time period. i.e

$f = 1 / T$

And

$T = T_{on} + T_{off}$

So by increasing the turn on time keeping the turn off time constant will change the total frequency of the system. Another way to change the frequency to increasing the total time period. In this method both the turn on time and turn off time are varied and hence the total time period of the system is increased.

However, in this proposed work the switching pulse is given in PWM form in which the total time period is varied by varying both turn on time and turn off time. But in this proposed work the ratio of the change in time for both turn on and turn off is same.

Performance Analysis on MATLAB

The designed circuit is analysed for three switching frequency 40Hz, 50Hz and 60Hz.

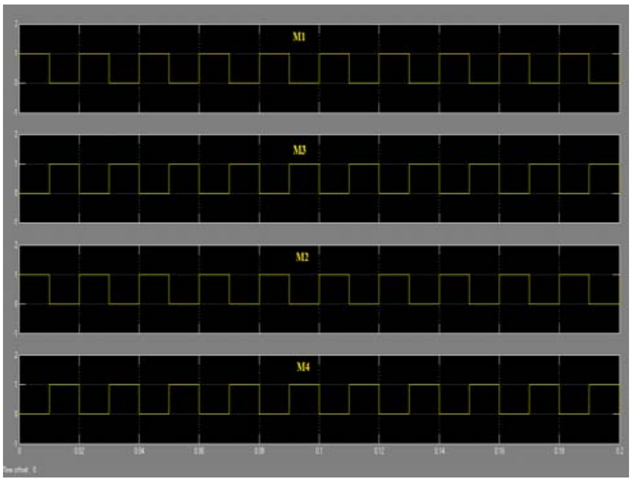

Figure 4: Switching pulse of the inverter switches at 50Hz

The figure-4 shows the switching characteristic of the switch of the inverter circuit. All the switches are operating at 50Hz. It can be easily seen that the pair of switches M1 and M2 are operating at same time and the other two switches are to be off state at that moment. Hence we can say that the pulse timing is accurate according to the requirement of the inverter switches. The same phenomenon occurs for the next pair of switches when switch M3 and M4 are in on state and the M1 and M2 are off state. In other words we can say that these pairs are 180 degree apart from each other.

The output of the circuit at various stages is shown in figure-5 with 50 Hz switching frequency.

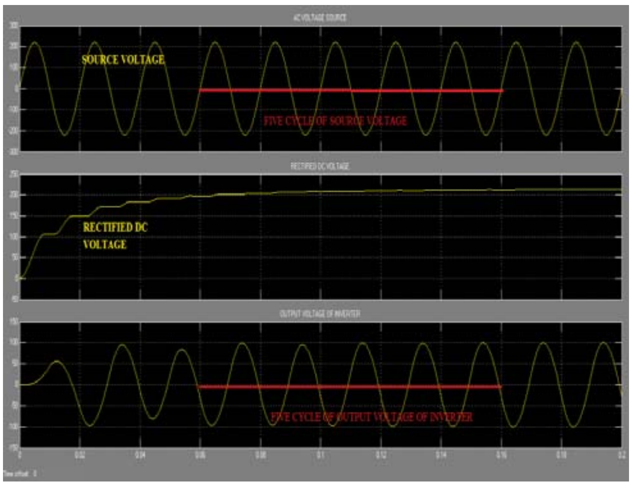

Figure 5: Input and output characteristic of the rectifier

and inverter circuit with filter at 50 Hz.

The figure-5 shows the input and output characteristic of the rectifier and inverter. First section of the graph shows the input voltage to the rectifier circuit while the second portion shows the rectified output voltage which is being filtered by the capacitor bank. This voltage is then feed to the inverter circuit. The inverter circuit input is the rectified circuit output. The parameter fed to the circuit is tabulated in table-2.

Table 2: Input and Output parameter at 50 Hz frequency of the simulate circuit

S.NO	PARAMETER	VOLTAGE (V) AT 50Hz	NUMBER OF CYCLES
1	INPUT	220	1
2	OUTPUT	100.2	1

From the figure-5 it can be easily illustrated that the inverter output frequency is same as that of the supply voltage. This is due to the reason that the both supply voltage and the switching frequency are of same frequency which is 50Hz.

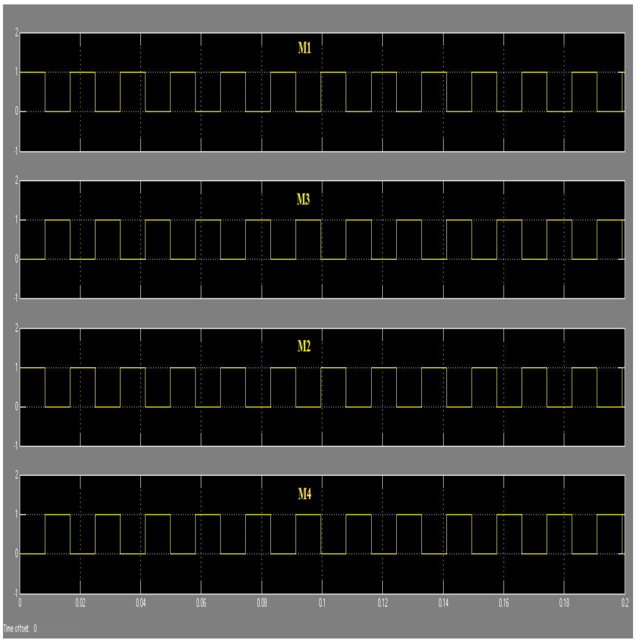

Figure 6: Switching pulse of inverter switches at 60Hz

The figure-6 shows the switching pulse of the inverter switches at 60Hz. From the figure-6 it will be easy to understand the effect of change in frequency at the output of inverter.

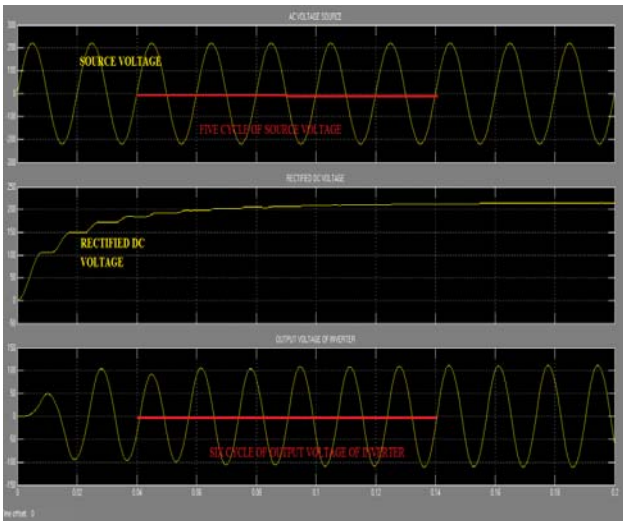

Figure 7: Input and output characteristic of the rectifier and inverter circuit at 60Hz

The figure-7 shows the characteristic of input and out parameter of the drive circuit and it can be easily seen that the variation in the input source voltage frequency and the inverter output frequency. By the use of filter circuit we achieve the sine wave output. The parameter fed to the circuit is tabulated in table-3.

Table 3: Input and Output parameter at 60 Hz frequency of the simulate circuit

S.NO	PARAMETER	VOLTAGE (V) AT 60Hz	NUMBER OF CYCLES
1	INPUT	220	5
2	OUTPUT	120.5	6

When the input supply voltage completes five cycles then at that time the output of the inverter completes six cycles. This shows that the input voltage is at 50Hz frequency while the output is at 60Hz. Also by calculating the time we can find the result that the input voltage is at 50Hz while the output voltage of the inverter is at 60Hz. Hence the frequency changes by applying the change in the switching frequency of the switches.

The circuit topology is also verified with the low frequency. 40Hz frequency is also applied across the switch of inverter. The figure-7 will show the switching waveform of 40Hz topology and it characteristic.

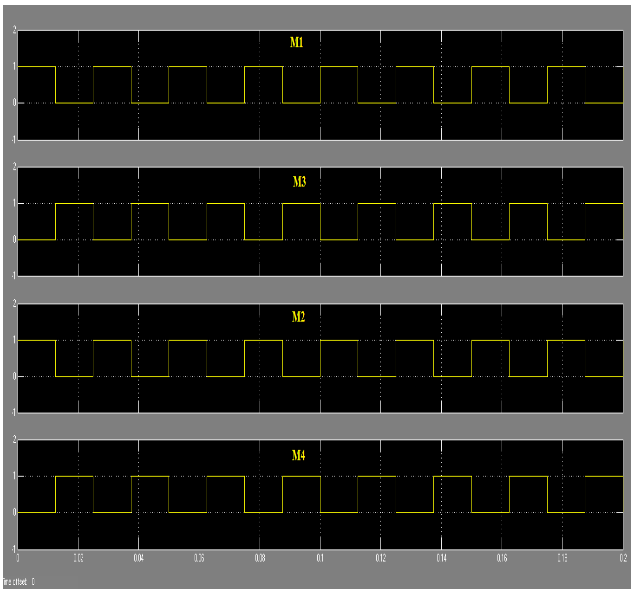

Figure 8: Switching pulse of inverter switches at 40Hz

The figure-8 shows the switching characteristic of the switch of the inverter circuit. All the switches are operating at 40Hz. it can be easily seen that the pair of switches M1 and M2 is operating at same time and the other two switches are to be off state at that moment. Hence we can say that the pulse timing is accurate according to the requirement of the inverter switches. The switching frequency can be illustrated with the respect of time. In the figure-8 graph the X axis behaves as the time axis while the Y axis behaves as the amplitude of the applied signal. So, all the switching frequency graphs is different with each other according to the time period. However, the characteristic of the pulses are same for any frequency. This shows the effectiveness of the switch.

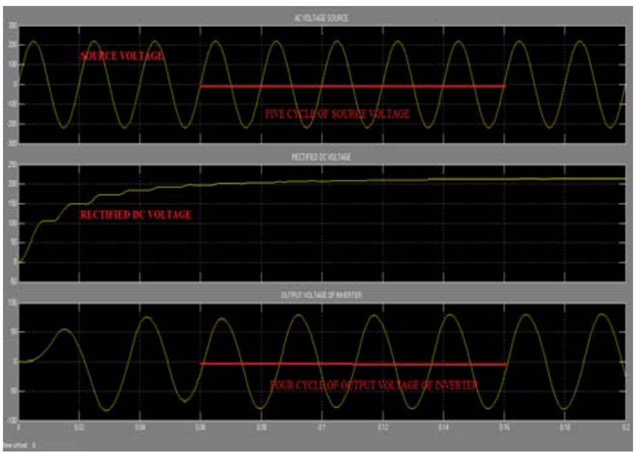

Figure 9: Input and output characteristic of the rectifier and inverter circuit at 40Hz

The figure-9 shows the input and output characteristic of the rectifier and inverter. First section of the graph shows the input voltage to the rectifier circuit while the second portion shows the rectified output voltage which is being filtered by the capacitor bank. This voltage is then feed to the inverter circuit. The inverter circuit input is the rectified circuit output. Figure-8 shows the pulse wave form and after that the inverter output is achieved which is shown in figure-9.

From figure-9 it can be easily illustrated that the filtered inverter output frequency is less as that of the supply voltage. The time period for completing one cycle of the inverter output is high as compared to the supply voltage. This is due to the reason that the supply voltage frequency is high as compared to the switching frequency of the inverter switches. The parameter for input and output of this configuration is tabulated in table-4.

Table 4: Input and Output parameter at 40 Hz frequency of the simulate circuit

S.NO	PARAMETER	VOLTAGE (V) AT 40Hz	NUMBER OF CYCLES
1	INPUT	220	5
2	OUTPUT	83.31	4

The frequency of the supply voltage is 50 Hz while the inverter output frequency is 40Hz. The result can be verified by calculating the time shown in the time axis of the graph. The supply source completes its five cycle in 0.1 sec while the inverter output completes its four cycle in 0.1 sec.

VFD Hardware Performance Evaluation

Using the MATLAB design simulation, VFD hardware was developed [10-20] and shown in figure-10. The components used and their specifications are tabulated in table-5.

Devendra Pal Singh et al. *International Journal of Science, Engineering and Technology,* 2016, Volume 4 Issue 2
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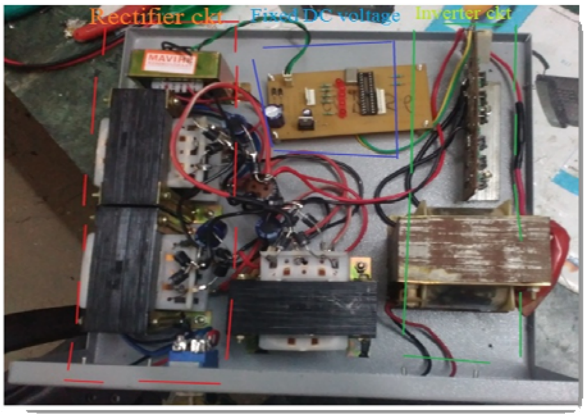

Figure 10: Hardware implemented circuit of VFD

Table-5: Bill of Material

S.No	Name of Component	Specification	Number of Units
1	Transformer	Step Down, 220/12, 5 A	3
2	Transformer	Step Down, 220/12, 1 A	1
3	Transformer	Step Up, 12/220, 5 A	1
4	Diode	HFA08TB60	6
5	MOSFET	IRF840	4
6	Transistor	BC547B	1
7	Transistor	BC557B	1
8	Capacitor	1000 uF	1
9	Capacitor	440 uF	3
10	Display	LCD	1
11	Power Plug	Anchor	1
12	Power socket	Anchor	2
13	Cable	Anchor	1 meter
14	Motor	Swing Machine	1
15	Cage	Iron	1
16	Micro Controller Chip	8085	1
17	Frequency Changer Manual	Havels	1
18	Cover Box Fabricated		1

The figure-10 shows the rectifier section of the circuit, inverter portion and the pulse generator section of the circuit. The circuit consists of five transformers. Two transformers are used for the rectifier circuit. One is connected at the output of the inverter. One transformer is used for the gate pulse to the MOSFET and one is for the circuit leakage current.

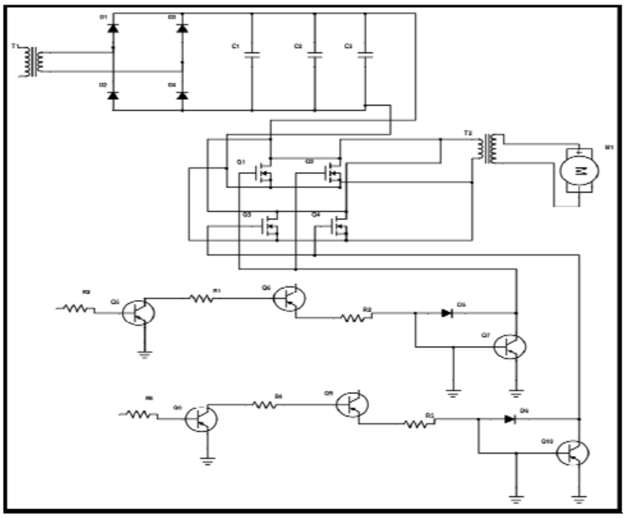

Figure 11: Circuit layout of VFD for hardware

Experimental Setup

The experimental setup consists of (i) VFD and (ii) Induction motor of 150 W. The experiment were conducted at 40Hz, 50Hz, and 60 Hz as input to the motor and voltage, current & RPM of the induction motor were measured using digital multi meter and tachometer.

Working of the hardware circuit

The hardware circuit works same as the simulated circuit. The circuit layout is shown in the figure-11. The input supply is given with the help of step down transformers T_1, T_2 , T_3. As it is known that the semi conductor devices do not operate at higher voltage due to the stress of voltage on it. It is unlikely to operate it at higher voltage. Hence, the step down transformer is used. This input is then fed to the rectifier bridge section so that it can convert the AC source into DC. The figure-12 shown illustrates the working of the hardware.

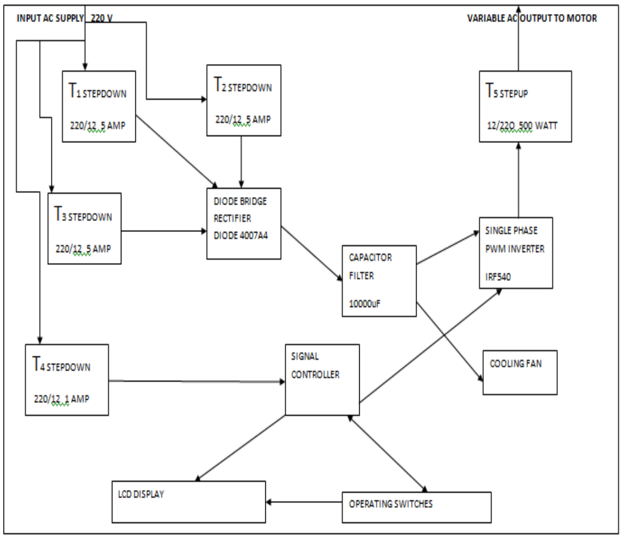

Figure 12: Block diagram of VFD for hardware

Torque Calculation

The Full load torque for induction motor is given as

$$T_{fl}=9550*P_{VA}/N_r*1000$$

Where $T_{f\,l}$ is the Full load Torque, P_{VA} is the Power in VA and N_r is the RPM of Motor

Result and Discussion

The experiments were performed on the developed VFD with 150 W inductions without having any load on the motor at 40Hz, 50Hz and 60 Hz frequencies. The measured, the measured values of speed (RPM), input voltage to motor (V) and current drawn by motor (A) is tabulated in table-6 for different frequencies.

Using voltage and current, the output power of the motor in Volt-Ampere has been calculated and also shown in table-6. Using equation (1) and values of P_{VA} and N_r from table-6, the torque developed has also been calculated and given in table-6.

Table 6: Experimental performance of VFD

Frequency in Hz	Speed (N_r) in RPM	Voltage in Volt	Current in Amp	Power in Volt Amp (P_{VA})	F.L Torque in N.m	% of Energy Saved
40	3700	80.31	0.483	38.8	0.1	26.93
50	4200	100.2	0.530	53.1	0.12	0
60	4800	110.25	0.575	63.4	0.126	NA

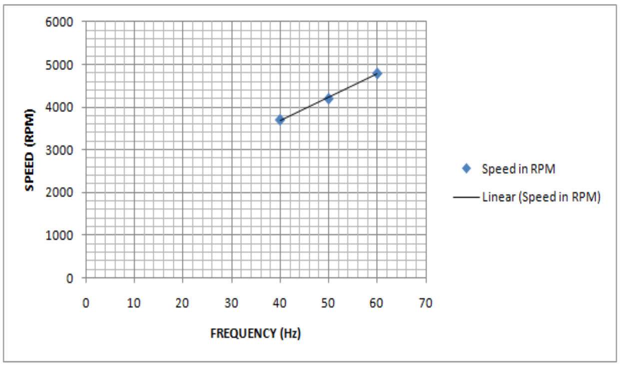

Figure 13: Frequency - Speed graph

The figure-13 shows the relation between the speed and frequency of the induction motor having VFD. The speed decreases as the frequency decreases.

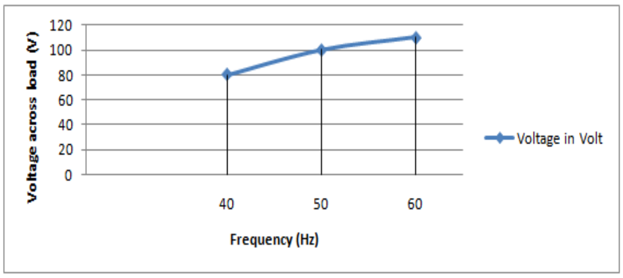

Figure 14: Frequency – Voltage graph

The figure-14 shows the relation between the frequency and output voltage of the induction motor. The variation in the frequency results change in voltage variation of the motor connected at the output of VFD.

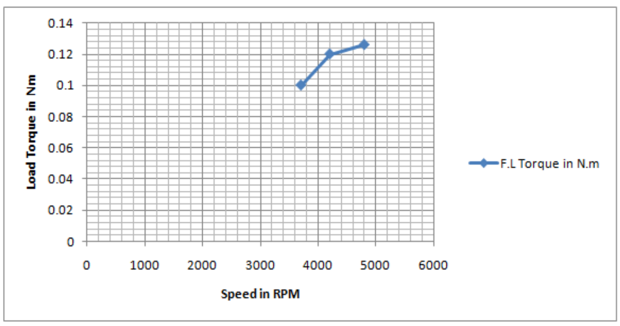

Figure 15: Speed – Torque graph

The figure-15 shows the graph of full load with respect to the speed of the motor. At full load the torque developed by the motor is maximum torque. At this point if we increase the speed then the torque increases till it does not reach the maximum torque. After that point the break down starts and torque start to decline. The figure-15 satisfies the criteria and results also show this. It can also been shown from table-6 that the VFD maintain the torque (V/A) nearly constant.

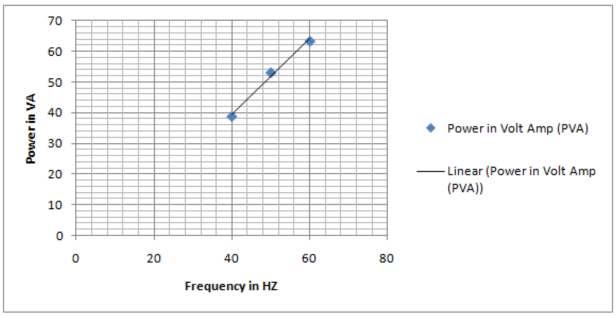

Figure 16: Frequency – Power graph

The results show that the output power decreases as the frequency decreases. In the present case, 26.93% power has been saved by decreasing the frequency for 50Hz to 40Hz.

Conclusion

The simulation results and the hardware implementation provide similar result. The speed and torque is controlled by the change in frequency which is satisfied by the hardware.

Due to change in frequency from $50H_z$ to $40H_z$ The frequency the power saved is 26.93%. Hence, the VFD in able to conservable the energy at variable on under loaded induction motors.

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