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Performance Evaluation of Inverter-equipped Drive to Regulate the Speed of Motor and Cooling Output of Air Conditioner

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Abstract. The Inverter-equipped Drive designed and constructed in this paper adopts a solid state electronic conversion system using Variable Voltage Variable Frequency (VVVF) control method coupled with AC – DC Converter and DC – AC Converter technology. The method involves the assemblage of DC Power Supply Unit, Monitoring and Control Units and Power Unit. The DC Power Supply Unit in the design supplies power to the entire system by converting the incoming 230VAC of fixed 50Hz into 150VAC through a step – down transformer. A bridge rectifier converts the transformer output voltage to a varying DC voltage, which in turn is passed through an electronic filter to convert it to an unregulated DC voltage. This DC voltage is then converted back into AC voltage through the use of IGBT electronic power transistors using Pulse Width Modulation (PWM) technique. The entire process is controlled by a microcontroller (PIC18F4431) which monitors the incoming voltage supply, speed set-point, DC link voltage, output voltage and current by sampling the current ambient air temperature and adjust the speed of the compressor appropriately. The results showed the corresponding actual speeds, frequencies, the current drawn by the motor, stator voltage, consumption power, and torque – characteristics are observed for both conventional and inverter-equipped drive air conditioner.

Key Words: Inverter-equipped Drive, Variable Voltage Variable Frequency (VVVF), AC – DC Converter, DC – AC Converter, Pulse Width Modulation (PWM), microcontroller.

1. Introduction

An inverter-equipped drive is used to control the speed of the compressor motor to drive variable refrigerant flow in an air conditioning system and to regulate the conditioned-space temperature. By contrast, traditional air conditioners regulate temperature by using a compressor that is periodically either working at maximum capacity or switched off entirely. Inverter-equipped air conditioners have a variable-frequency drive that incorporates an adjustable electrical inverter to control the speed of the motor and thus the compressor and cooling output. Inverter enables the fixed-speed motor to operate at variable speeds.

An inverter- equipped drive is competent of adjusting both the speed and torque of an induction motor. It consequently provides unremitting range process speed control (as compared to the discrete speed control that gearboxes or multispeed motors provide). Most of variable-frequency drive (VFD) is used for calculating the speed of a rotational or linear alternating current (AC) electric motor by controlling

the frequency of the electrical power supplied to the motor. The multispeed process and versatile operation are provided by controlling the speed of these motors [1].

A typical inverter receives 220 - 230 VAC, three-phase, 50 Hz input power and in turn provides the desired voltage and frequency for a given speed to the motor. The two common inverter types are the variable voltage inverter (VVI) and current source inverter (CSI). AC drives convert AC to DC, and then through various switching techniques and advance technology invert the DC into a variable voltage, variable frequency output. The drive configuration by design and operation consists of the following components: Converter, DC Link and Control logic generation using microcontroller, DSP, etc [2].

1.1 Applications and Benefits of Inverter-equipped Drives
With advances in microelectronics and control technology over the recent years [9-10], Inverter-equipped drives or Variable Frequency Drive (VFD) has become an efficient and reliable means of controlling motor speed. Facilities that install VFDs will use less energy, cut operating costs, and even improve process precision. VFDs eliminate the need for expensive and energy-wasting throttling mechanisms such as control valves and outlet dampers. In addition to lowering electricity costs, VFDs reduce wear and tear on motors and related components - decreasing maintenance costs and prolonging equipment life. A motor without a VFD operates at a constant speed. When full power isn't needed, the motor can cycle on and off frequently in an attempt to match the load. This creates unnecessary wear and reduces equipment life.

A major benefit of VFDs is their "soft-start" capability that gradually ramps up a motor's operating speed at startup and greatly reduces the stress on components. On typical startup, a constant-speed motor is subject to high torque and electrical surges that can reach up to ten times the full current load. The disproportionate benefits of controlling motor speed should be of interest to all building owners and managers. VFDs can improve process efficiency and occupant comfort. For example, VFDs allow greater control of machine tool drives and processes such as water distribution, aeration, and chemical feed. In wastewater treatment plants, VFDs on aeration blowers can maintain consistent concentrations of dissolved oxygen.

In heating, cooling, and ventilation (HVAC) applications, VFDs can improve occupant comfort by modulating the flow of air throughout a building. VFDs further improve occupant comfort by reducing the noise output of fans and pumps. In addition to the energy savings, VFDs provide longer equipment life because systems are not running at 100 percent all the time.

1.2 Variable Frequency Drive Mechanism
There are different methods of speed control of induction motor using variable frequency control strategy such as pole changing, frequency variation, variable rotor resistance, variable stator voltage, constant V/F control, slip recovery method etc. Variable frequency drives are electronic systems that convert AC to DC and then simulate AC with a varied frequency resulting to changing the speed of the motor. There are three basic designs configuration for variable frequency AC motor controls. There are Six Step Inverter (variable voltage source), Current Source Inverter, and Pulse Width Modulated Inverter (PWM; constant voltage source). Each type of the three possesses unique electrical characteristics that should be considered in the application for load requirements, motor selection, system operating efficiency, and power factor. Pulse Width Modulated (PWM) is the most prevalent in terms of application [3].

Ideally, the synchronous speed of induction motor is directly proportional to the frequency and inversely proportional to the number of poles of the motor as shown in equation 1. Since the number of poles is fixed by design which is two poles for this research, the best way to vary the speed of the induction motor is by varying the supply frequency.

$$N_S \alpha \frac{f}{p} \tag{1}$$

$$N_S = \frac{120f}{p} \tag{2}$$

Where, f = Frequency in Hz, P = Number of Poles

The speed of the motor shaft with rated voltage and line frequency applied at full load is so called base speed. By changing the frequency of the motor above or below frequency; the motor can operate above or below base speed. The relationships between the applied voltage (V), frequency (f) and torque (T) of the induction motor are given as shown in Equation 3.

$$Torque(T) = \frac{Voltage(V)}{Frequency(f)} I \tag{3}$$

Equation 3 implies that when the ratio of V/f is constant, the torque is constant and when the voltage (V) is constant and only the frequency (f) varies, the torque is inversely proportional to the frequency provided the motor current is constant.

1.3 Constant Torque Operation

Many energy efficient drives require a constant torque output which can only be achieved if the air-gap flux in the motor is maintained constant. From the classical law of Faraday, the electromotive force (E.M.F) induced in winding of motor is proportional to the rate of change of the magnetic flux. Therefore, as the applied frequency is varied back or forth, the rate of change of flux is also reduced or increased accordingly.

As a matter of fact, when the applied frequency is reduced, the EMF, and therefore the operating voltage (if the stator impedance is negligible); must be reduced proportionately or the saturation flux density is exceeded, resulting in excessive iron loss and magnetizing current. More so, when the applied frequency is increased, the operating voltage should be increased proportionately in order to maintain the magnetic flux density. An ac induction motor produces torque by virtue of the flux in its rotating field. Keeping the flux constant will enable the motor to produce full load torque. This is accomplished by maintaining a constant voltage-to-frequency ratio applied to the motor when changing the frequency for speed control.

Because of the physics of the induction motor the preferred method of controlling its speed is to vary the frequency of the AC voltage driving the motor. As the number of pole is not variable, varying the supply frequency would result in variation in the speed of motor. Variation of voltage should be in proportion to supply frequency so that torque developed is constant over the speed range.

The following Equation (4) is used for calculating motor speed:

$$Synchronous\ Speed = \frac{120 \times frequency}{number\ of\ poles} \tag{4}$$

Normal electric power in Nigeria is supplied at 50 cycles per second, or 50 hertz (Hz). A common motor rotational speed, that is revolution per minute (rpm) at this frequency are 3,000 rpm, 1,500 rpm, 1,000 rpm, or 750 rpm, depending on how the motors are wound (number of poles). Once the motor is fabricated, the only variable that can change in the synchronous speed Equation is the frequency (Hz) of the power supply. The motor speed is directly proportional to the frequency. Rather than supplying the electric motor with a constant frequency of 50 Hz, the VFD takes the electrical supply from the utility and changes the frequency of the electric current which results in a change of motor speed.

VFD controls both frequency and voltage simultaneously to keep a constant ratio of volts and Hertz so that the motor sees a constant current flow similar to full speed conditions. VFDs are not capable of increasing voltage so as the frequency increases the torque starts to decrease. At some point as the speed increases there will not be enough torque to drive the load, and the motor will slow even with increased frequency as presented in Equations 5 and 6 according to [1], [4], [5], [6] and [7].

$$\text{Magnetic flux } \alpha = \frac{Voltage}{frequency} = \text{constant} \tag{5}$$

$$Torque(T) = \frac{Voltage(V)}{frequency(f)}.current(I) \tag{6}$$

1.4 Affinity Laws

Affinity Laws are used in motor driven appliances, hydraulic and HVAC system to express the relation between several variables involved in pump, compressor, hydraulic turbines and fan performance (such as shaft speed, and power). The laws of affinity (Equations 7 – 9) according to [8] states thus;

Flow rate, Q is directly proportional to rotational shaft speed, N of the induction motor

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \tag{7}$$

Torque, T required by the machine is proportional to speed squared of motor

$$\frac{T_2}{T_1} = \left(\frac{N_2}{N_1}\right)^2 \tag{8}$$

Motor Shaft Power, P of the system is proportional to the cube of the shaft speed

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3 \tag{9}$$

From this affinity laws, it is shown that flow rate is directly proportional to speed of the motor, while torque required is proportional to the square of speed. Most importantly from the energy savings perspective which is the major focus of this research is that the power consumed by the system is proportional to the cube of speed. This means even minimal reductions in speed can provide savings in consumed power which is undoubtedly vindicated in this research. A reduction in speed produces more than straight-line savings due to the affinity laws that describe energy use in motors.

1.5 Constant Torque Operation for Developed Drive

The induction motor of this developed drive produces torque by virtue of the flux in its gyratory field. Keeping the flux constant enables the motor to generate full load torque. This is achieved by maintaining a constant voltage-to-frequency ratio applied to the motor when varying the frequency for speed control. Variation of voltage is in proportion to supply frequency so that torque developed is constant over the speed range. The torque values are determined in this paper using Equation 10 according to [1], [4], [5], [6] and [7].

$$Torque(T) = \frac{Voltage(V)}{frequency(f)}.current(I) \tag{10}$$

The aim of this work is to analyze the performance evaluation of inverter-equipped drive to regulate the speed of motor and cooling output of air conditioner. The objectives are to design and construct a frequency adjustable induction motor; to apply artificial intelligence technique to regulate air conditioner; and to compare the performance test and experimental results of inverter-equipped drive with conventional air conditioner.

Motor-driven appliances used in Heating, Ventilation, and Air Conditioning (HVAC), refrigeration, washing machine, pumping machine etc are the highest energy consumers in both the residential and commercial sectors. Fixed speed motors in the traditional air conditioners serve majority of applications. These devices usually result in inefficient of operation, great deal of energy loss and wasted because of their throttling action. Inverter-equipped drive proposed by this research reduces electrical energy consumption by adjusting a motor's speed to match the required load.

By outfitting the air conditioner with inverter-equipped drive, facilities can control the equipment's output to match the operation's needs, saving energy when full output is not required. This operation technique of traditional air conditioner creates a lot of challenges that are considered and addressed by this research. The challenges include high consumption of energy and poor efficiency by the machine, high electricity bill costs, occupants discomfort through noise output from fan and compressor, creates unnecessary wear and tear on motors and related components, reduces equipment life, high operating costs, requires expensive and energy-wasting throttling mechanisms.**.** There is fluctuation of temperature due to ON/OFF switch of compressor which affects the cooling comfort of the conditioned space.

 Inverter-equipped drive designed and constructed in this research adopted Variable Voltage Variable Frequency (VVVF) control method. The drive is designed to regulate the frequency and speed of the compressor motor, to control variable refrigerant flow in an air conditioning system and to vary the conditioned-space temperature, thus improve cooling output of the system. This developed drive air conditioner uses less energy, cuts operating costs, and even improves process precision.

2. Design and Methodology

The design arrangement of inverter-equipped drive in this paper is systematically classified into three broad units (as revealed on Figures 1 and 2). These include:
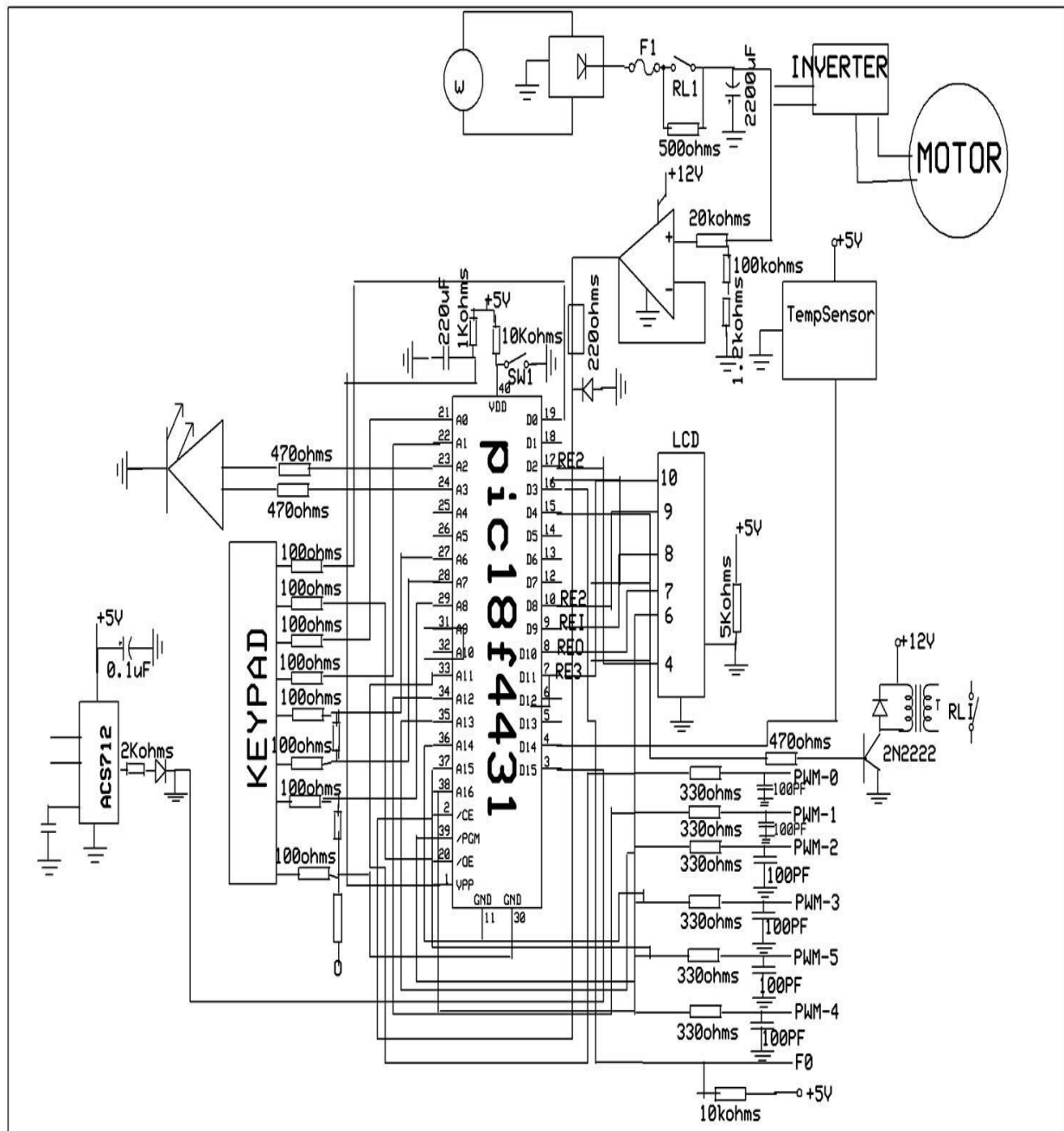
   i.   DC Power Supply Unit
  ii.   Control and Monitoring Units
 iii.   Power Unit

The DC Power Supply Unit in this design supplies power to the entire system through three major components or subunits: Step – Down Transformer, Filtering Capacitor and Adjustable Regulators. The monitoring and control units applied in this research include the microcontroller, voltage sensor, temperature sensor, current sensor and user interface units to control large or multifaceted set-up operations centers in this system with some extent of automation.

The power unit adopted for the research controls the central activities of the system with the following sub units: 6 - IGBT transistors, IGBT Drive, Bridge Rectifier, Relay, Filtering Capacitor and Limiting Resistor.
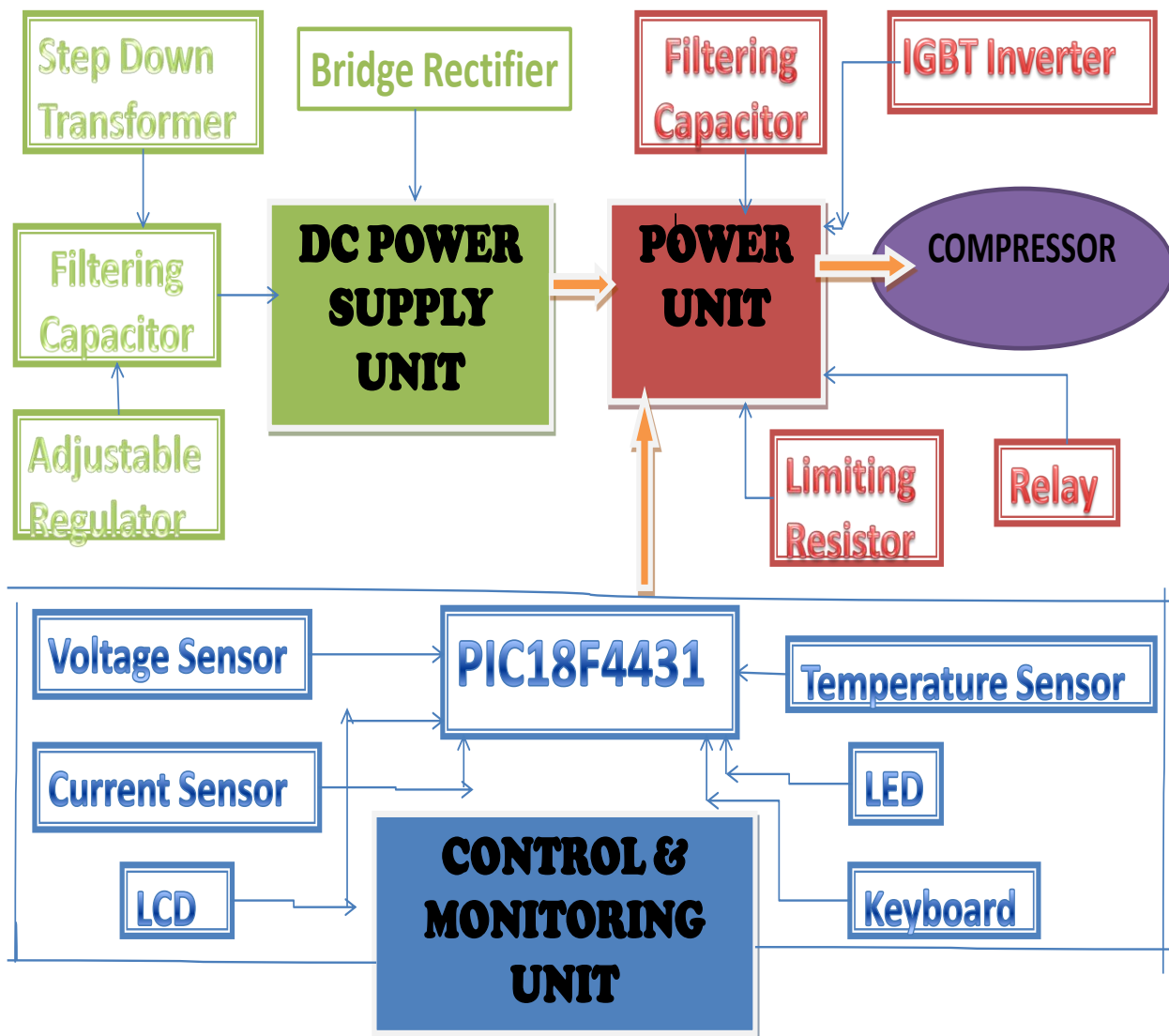
Figure 1: The Block Diagram of Inverter-equipped Drive

Figure 2: Inverter-equipped Drive Model Circuit Diagram

The design arrangement involves the assemblage of DC Power Supply Unit, Monitoring and Control Units and Power Unit. The DC Power Supply Unit supplies power to the entire system by converting the incoming 230VAC of fixed 50Hz into 150VAC through a step – down transformer. A bridge rectifier converts the transformer output voltage to a varying DC voltage. This DC voltage is afterward converted back into AC, this alteration is characteristically achieved through the use of IGBT electronic power transistors using Pulse Width Modulation (PWM) technique of Power Unit. The output voltage is turned on and off at a high frequency, with the duration of on-time, or width of the pulse, controlled to approximate a sinusoidal waveform.

The entire process is controlled by a microcontroller (PIC18F4431) which monitors the incoming voltage supply, speed set-point, DC link voltage, output voltage and current by sampling the current ambient air temperature and adjust the speed of the compressor appropriately. The microcontroller is programmed to provide variable frequency PWM signal that controls the applied voltage at gate drive produces required PWM frequency at the output of power inverter. The IGBT Inverter controlled by microcontroller produces electronically the desired sinusoidal waveform at a particular frequency that fed in the compressor motor.

3. Performance Test and Experimental Results of Inverter-Equipped Drive

The inverter-equipped drive successfully designed and constructed in this research is connected with a conventional air conditional and set running at different periods under steady power consumption. The drive is implemented by a microcontroller (PIC18F4431) based PWM inverter and programmed using C language. The speeds of the induction motor are varied from 1440RPM to 4200RPM at a corresponding frequency range from 24Hz to 70Hz. The constructed drive is tested for a 3 phase, 415 Volts, 1.5 H.P. Induction Motor for different frequencies, speeds and load reading.

The experimental results showing the corresponding actual speeds, frequencies, the current drawn by the motor, stator voltage, consumption power, and torque – characteristics are observed for both conventional air conditioner and air conditional with inverter-equipped drive as revealed in Tables 1 and 2 as well as Figures 3 - 5.

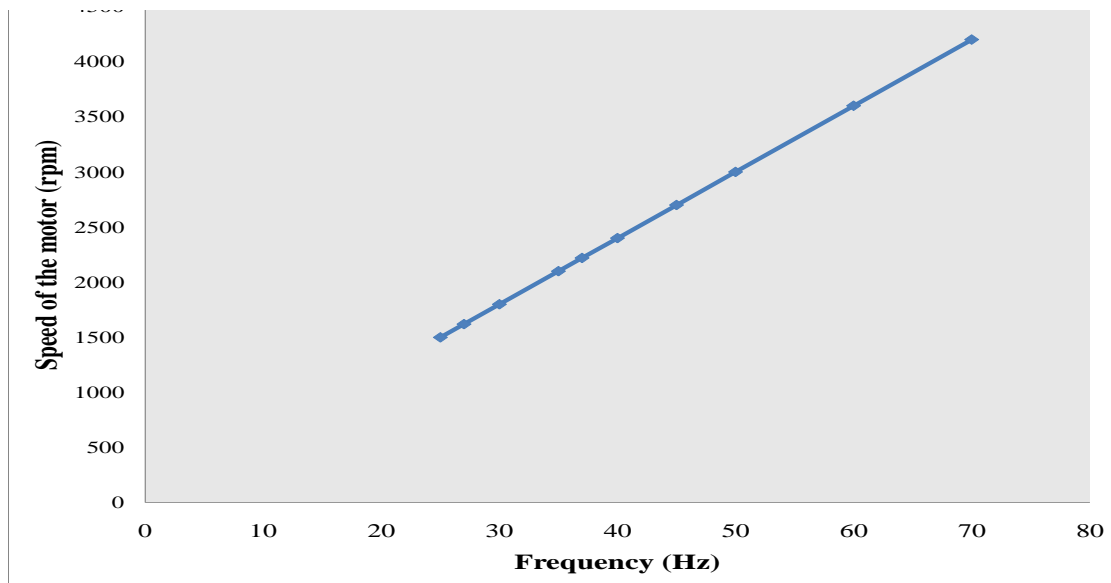**Table 1:** Experimental Results of Conventional Air Conditioner at Constant Frequency

| S/N	Time (hr)	Room Temp. (^{0}C)	Energy Meter Reading (kWh)	Air Flow Rate (m^3/h)	Speed (rpm)	Frequency (Hz)
1	8:45am	25	1.5	50	3000	50
2	9:42am	24	2.5	100	3000	50
3	10:44am	24	4.0	150	3000	50
4	11:40am	24	5.5	200	3000	50
5	12:46pm	24	7.0	250	3000	50
6	1:41pm	28	8.5	300	3000	50
7	2:43pm	30	10.0	350	3000	50
8	3:45pm	30	11.5	400	3000	50
9	4:40pm	27	13.0	450	3000	50
10	5:42pm	26	14.5	500	3000	50
11	6:47pm	26	16.0	550	3000	50
12	7:50pm	25	17.5	600	3000	50
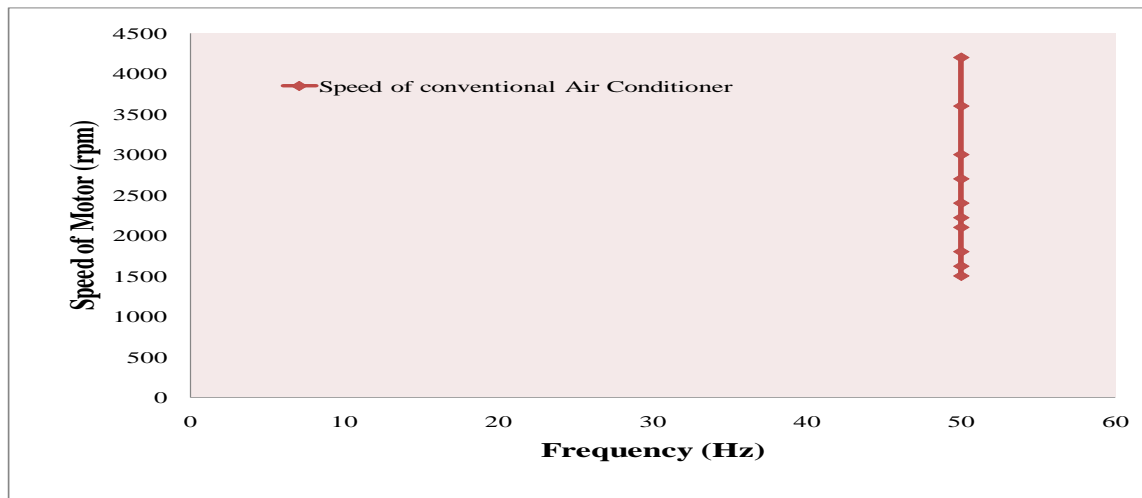
Figure 3: Speed- Frequency Characteristics of Conventional Air Conditioner.

Table 2: Experimental Results of Inverter-equipped Drive Air Conditioner

S/N	Time (hr)	Room Temp. (^{0}C)	Energy Meter Reading (kWh)	Air Flow Rate (m^3/h)	Speed (rpm)	Frequency (Hz)
1	8:05am	25	1.0	50	1440	24
2	9:00am	24	1.1	100	1620	27
3	10:10am	23	1.2	150	1800	30
4	11:07am	22	1.3	200	2100	35
5	12:05pm	24	1.4	250	2220	37
6	1:01pm	28	1.5	300	2400	40
7	2:05pm	30	1.7	350	2700	45
8	3:07pm	30	1.9	400	3000	50
9	4:03pm	27	2.2	450	3300	55
10	5:06pm	26	2.5	500	3600	60
11	6:00pm	26	2.8	550	3900	65
12	7:05pm	25	3.1	600	4200	70

Figure 4: Speed - Frequency Characteristics of Inverter-equipped Drive
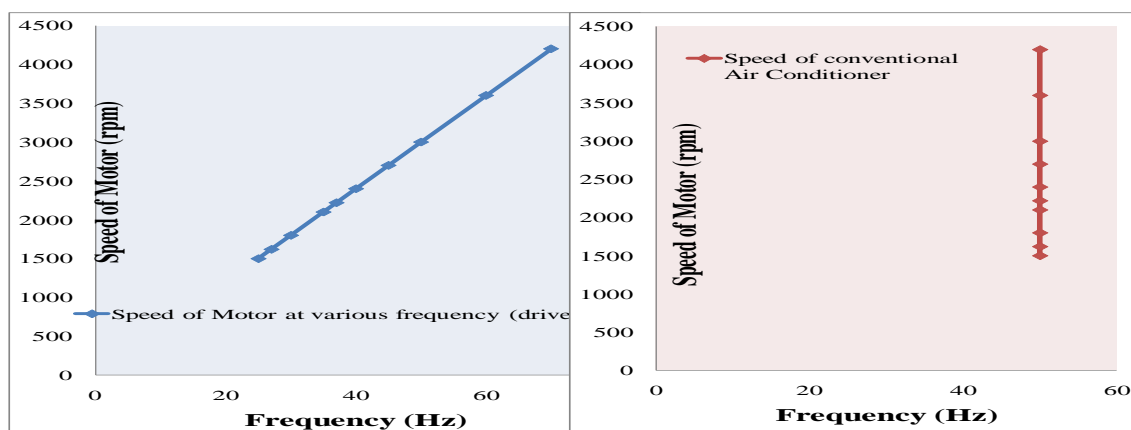
Figure 5: Experimental Results showing Speed – Frequency Characteristics of Conventional and Inverter-equipped Drive Air conditioner

The results show that the conventional air conditioner that mechanically applies the throttling devices, valves and dampers when flow is controlled without regulating the motor speed, it runs incessantly at complete speed. Since HVAC systems infrequently necessitate highest flow, a
system working devoid of speed control wastes noteworthy energy over a good number of its operating time. The energy efficient drive air conditioner is able to save a significant amount of energy due to the variation of the frequency that eventually translates to the vary speed of the motor of the compressor and consequent energy saving of the machine.
The Table 2 shows the observed readings when the constructed drive is coupled with air conditioner. The table elucidates that there is variation in the frequency applied which results to the variation in the speed of the motor. Seeing that the speed of an induction motor is proportional to the frequency of the AC, the compressor can at the moment run at different speeds.

4. Conclusion

The inverter-equipped drive designed and constructed in this research provides reliable, efficient, cost-effective variable-frequency (V/Hz) control of air conditioner compressor motors. The constructed drive was realized for efficient power management using intelligent control system. This significantly regulates the frequency, speed, voltage, torque, power and reduces the noise output of the fan and compressor for efficient performance at low power consumption.

The developed drive design involved the assemblage of DC Power Supply Unit, Monitoring and Control Units and Power Unit. The DC Power Supply Unit in the design supplies power to the entire system. A bridge rectifier converts the transformer output voltage to a changeable DC voltage. This DC voltage is subsequently transformed back into AC through IGBT electronic power transistors using Pulse Width Modulation (PWM) method of Power Unit. The microcontroller (PIC18F4431) is programmed to provide variable frequency PWM signal that controls the applied voltage at gate drive produces required PWM frequency at the output of power inverter. The IGBT Inverter controlled by microcontroller produces electronically the desired sinusoidal waveform at a particular frequency that fed in the compressor motor.

Acknowledgment

References
[1] Atul, M. G. and Nitin, R. B. (2013). Control of Air Flow Rate of Single Phase Induction Motor for Blower Application Using V/F Method. *International Journal of Engineering Sciences & Emerging Technologies,* 6(1):102-112. Retrieved on July 12, 2014 from www.ijeset.com.
[2] Shilpa, A. L. and Sarabh, M. I. (2013): Speed Monitoring and Control of Three Phase Induction Motor for Batching Motion System of Textile Industry. *International Journal of Engineering Research and Applications,* 3(6):2090-2095. Retrieved on August 20, 2014 from www.ijera.com.
[3] NRCS (2010). United States Department of Agriculture Natural Resources Conservation Service Montana Engineering Technical Note, 14, pp. 36. Retrieved on 20th June, 2014 from www.nrcs.com
[4] Thida, W.; Nang, S. and Hnin, N. M. (2008). Analysis of Variable Frequency Three Phase Induction Motor Drive. *World Academy of Science, Engineering and Technology*, 2(6):609-611. Retrieved on November 20, 2014 from www.citeseerx.ist.psu.edu
[5] Jatin, J. P.; Kubavat, A.M. and Jhala, M.B. (2014). Speed Control of a Three Phase Induction Motor using PWM Inverter. *International Journal of Engineering Development and Research*, 2(1):503 – 507. Retrieved on August 13, 2014 from www.ijedr.org.
[6] Shalini, N. M.; Aspalli, M. S. and Hungund, P.V. (2012). Speed Control of Three Phase Induction Motor Using VLSI. *International Journal of Advanced Information Science and Technology (IJAIST)*, 8(8):20-22. Retrieved on October 2, 2014 from www.ijaist.com
[7] Atul, M. G. and Nitin, R. B. (2014). Performance Analysis of Operating Characteristic of Single Phase Induction Motor with Blower Application. *International Journal of Advances in Engineering & Technology* 6(6):2548-2555. Retrieved on July 12, 2014 from www.e-ijaet.org

[8] Neetha, J.; Mohandas, R. and Suja, C. R. (2013). Energy Saving Mechanism Using Variable Frequency Drives. *International Journal of Emerging Technology and Advanced Engineering,* 3(3):784 - 790. Retrieved on 20th June, 2014 from www.ijetae.com.

[9] Adagunodo T.A., Ajigbotosho J.J., Obafemi L.N., Usikalu M.R., Akinwumi S.A., Ayara W.A. (2018). Construction of an in-situ Smart Device that Measures some Basic Environmental Factors for Agricultural Monitoring. IOP Conference Series: Earth and Environmental Science, 173: 012023. https://doi.org/10.1088/1755-1315/173/1/012023.

[10] Ayara W.A., Usikalu M.R., Akinyemi M.L., Adagunodo T.A., Oyeyemi K.D. (2018). Review on Li-Fi: an Advancement in Wireless Network Communication with the Application of Solar Power. IOP Conference Series: Earth and Environmental Science, 173: 012016. https://doi.org/10.1088/1755-1315/173/1/012016.