Variable Voltage Variable Frequency Drive for Single-Phase Motor and its Application

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Abstract: ***In this paper, the design & implementation variable voltage variable frequency (VVVF) drives scheme base on sinusoidal pulse width modulation (SPWM) technique for a single-phase induction motor. The main objective was to evaluate the popular variable speed drive schemes as they operate in their most efficient mode of under different loading conditions. The considered schemes included phase control, variable frequency drives, voltage control and also, with the mathematical expression. The VVVF technique used extensively in the industry as it provides the accuracy required at minimal cost.***

Keywords: Variable Frequency Drive (VFD), Rotating Magnetic Field (RMF), Electromagnetic Interference (EMI), Pulse Width Modulation (PWM), Insulated Gate Bipolar Transistor (IGBT), Gate Driver, Inverter.

1. Introduction

The speed control of AC motor evolved very rapidly with advances in power electronics technology. Applications that were dominated by DC motor became most suited for AC motors as a more economical alternative. Three-phase motors, however, the initial prime developments for candidates are more significant impact on high-power application in industries. AC Single-Phase Induction Motors (SPIMs) are well-known for their low cost and versatility. Compared to three-phase induction motors, Single phase motors lack the self-starting capabilities and more sensitive for loading conditions.

For applications with varying loads, a variable-speed drive is must since it can achieve up to 50% in energy savings. Drives are widely used in ventilation systems for large buildings, variable frequency motors on fan save energy by allowing the volume of air moved to match the system demand. They are also used in pumps, elevator, conveyor and machine tool drives. Moreover, there are three commonly known techniques for AC motors drives; namely, variable frequency, voltage control, and variable rotor resistance. Several studies have been conducted to analyze the performance of the different drives.

Nomenclature

R1, X1	Resistance and reactance of the stator
R'2, X'2	Resistance and reactance of the rotor
X_m	Mutual reactance
τ_{ind}	Induced torque
V_{TH}, R_{TH}	Thevenin voltage and resistance
ω_m, ω_{sync}	Motor speed and synchronous speed in rad/sec
Z_F, Z_B	Forward and backward impedance
I	Stator current
P_{AG}, $P_{AG,F}$, $P_{AG,B}$	Air-gap power: total, forward and back-ward
P_{in}, P_{out}	Input and output power
P_{conv}	Converted power
P_{RCL}	Core losses
P_{rot}	Rotational losses
P_s	Power savings
V	Phase voltage
f	Line frequency in Hz ($\omega=2\pi f$)
n_m, n_{sync}	Motor speed and synchronous speed in rpm
τ	Torque
s	Slip
p.f.	Power factor
η	Efficiency

In this paper, the mathematical model's development for theory of the steady-state operation of SPIM is presented. Experimental test was then performed in order to determine the motor parameters. The motor-winding parameter was identified by the torque-speed characteristic of motor. The consumption of power under the various loading condition was analyzed by experimentally and via modelling technique by controlling the different loading conditions to the optimal mode of operation. Furthermore, the fan application was analyzed in order to provide a real-life application and this kind of analysis important for energy efficiency

2. I.M.-Model

- The application, there is insufficient information available about the motor parameters, such as inductance and winding resistance, it is compulsory to eliminate the following three classical tests: Locked-rotor test, DC test and No-load test. These experimental tests are based on the single-phase induction motor static RC equivalent circuit model shown in figure-1. This model is based on double-revolving-filed theory. This theory states that a stationary pulsating magnetic field can be expressed as two rotating magnetic fields (forward and backward) of the same magnitude but with different direction. The effective torque that is produced is then practically equal to the resultant sum of torque components due to each of the two magnetic fields.

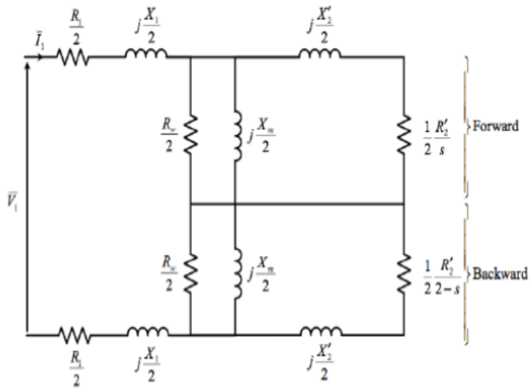

Figure 1: Equivalent Circuit of a Single-Phase Induction Motor

Since the purpose of this study was to analyze the energy efficiency of the drives discussed earlier, it was not necessary to analyzed the dynamics of the induction motor. This is where the d-q model would have been necessary. The motor-winding parameters found experimentally are shown in Table 1.

This section describes the relationship of the motor's torque, power and speed. Chapman derived the formula that describes the induced torque from an analysis of the three-phase motor's equivalent circuit. This formula can be applied to the single-phase motor using a 1/3 scaling factor since the torque is additive. Thus, this formula was applied here using the parameters presented in Table 1. In addition, the ideal torque-speed characteristic was compared with experimental data for validity.

Table 1

Parameter	Value
Main winding stator resistance(ohms)	15.8971
Main winding stator/rotor resistance(ohms)	17.9800
Main winding stator/rotor inductance(H)	0.0477
Main winding rotor resistance(ohms)	12.7190
Main winding mutual resistance(ohms)	223.1849
Main winding mutual inductance(H)	0.5920

It should be noted from Equation (1) that the produced torque is dependent on the slip (motor speed), operating frequency as it affects the reactance (X=jωL), and the phase voltage, V_ϕ. The resistance also plays a role, but it was assumed constant for purposes of this study. Most economical SPIMs are of the squirrel-cage type, where the rotor resistance is practically fixed. Wound-rotor motors may provide access terminals to change their effective rotor resistance. The dependence of τ_{ind} on n_m, V_ϕ, f and R2 permits the reverse logic of adjusting n_m for a given τ_{ind} (load) using V_ϕ and f.

$$\tau_{ind} = \frac{\frac{V_{TH}^2 R_2}{s}}{\omega_{sync}\left[\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2\right]} \quad (1)$$

where

$$V_{TH} \approx V_\varphi \frac{X_M}{X_1 + X_M}$$

$$R_{TH} \approx R_1 \left(\frac{X_M}{X_1 + X_M}\right)^2$$

Equation (1) was utilized to create the torque-speed characteristic curve presented in Figure 2, where $s = (n_m - n_{sync})/n_{sync}$.

In physical experiments, the motor was operated under a variable load and the torque was measured at the corresponding speeds (see Figure 2). The rated motor voltage (115 V) and nominal frequency (60 Hz) were used in this test. Figures 3 and 4 show the simulation results for the same motor for variable f and V_ϕ, respectively.

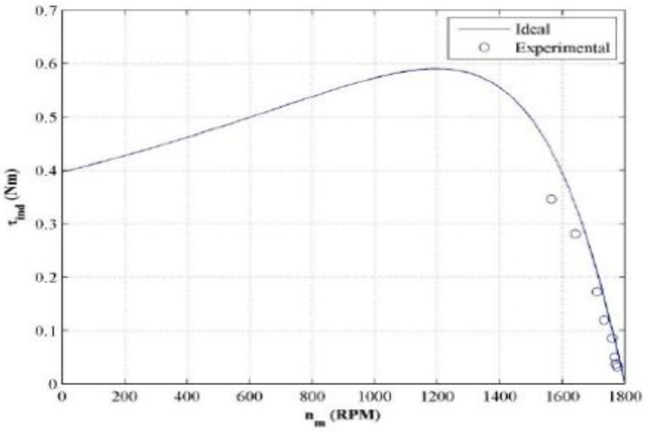

Figure 2: Induction-Motor Torque Characteristic

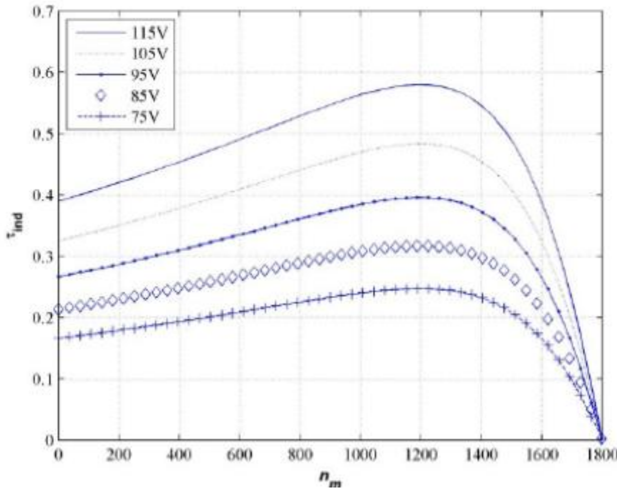

Figure 3: Torque-Speed characteristic for Different Voltages

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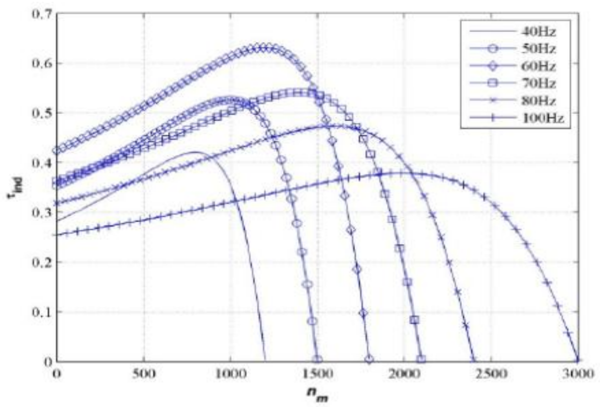

Figure 4: Torque-Speed Characteristic for Different Frequencies

3. Basic operation of VFD

VFD operation requires three basic sections: the rectifier, dc link, and Inverter. The AC power supply produces a sinusoidal wave. The positive voltage causes a current to flow in one direction and a negative voltage causes a current to flow in opposite direction. A large amount of energy is transmitted efficiently over great distances.

Before rectifier, line filtering is done to reduce the noise entering the equipment from commercial power lines or noise generated from electronic equipment. Common mode chokes, line bypass capacitors and Metal Oxide Varistors (MOVs) are generally used as filter devices for suppressing AC Electromagnetic Interference (EMI). There are two modes, differential mode (line to line) and common mode (line to ground). Filters are designed to suppress Radio Frequency Interference (RFI) and EMI that exists in these modes. The most frequently encountered is Common mode interference and hence common mode chokes are used most often. Common mode chokes suppress common mode noise and thereby influence the performance of the filter block.

The rectifier which is in the form of bridge comprising of six diodes (full wave) converts the incoming AC voltage (power) from the power supply into a pulsating DC voltage (power). This rectified DC voltage flows and the DC link block that contains a capacitor. The capacitor accepts this voltage (power) from the rectifier stores it and delivers a smooth voltage to the inverter block. Inductors, chokes or similar things add inductance and provide more smoothening to output voltage.

The final section of VFD is an inverter. The inverter requires a stable dc voltage at its input. A voltage regulator circuit provides this stable voltage. A voltage regulator converts the unregulated dc voltage obtained from the bridge rectifier into regulated dc voltage. It provides a constant dc output voltage and contains a circuitry that continuously holds the output voltage at the desired value. The control circuitry is basically a feedback loop between the input and output of the voltage regulator circuit that monitors the output voltage.

The inverter contains power transistors that deliver power to the motor. IGBT is a common choice in modern VFDs. It can switch ON and OFF several thousand times per second. The IGBT uses PWM (Pulse Width Modulation) technique to simulate a sinusoidal current at the desired frequency to the motor. The inverter requires a stable dc voltage at its input. Hence, the rectified output of the bridge rectifier which is filtered using DC link is made constant using a voltage regulator circuit.

A driver circuit is used to drive the gate of the IGBT's. This circuit comprises of TLP250 and IR2110. TLP250 is an 8-pin power MOSFET or IGBT gate drive optocoupler consisting of an LED and photo detector. IR2110 is a high voltage; high speed Power MOSFET/IGBT driver with independent high and low side output channels. The drain terminal is connected to high voltage in the system and hence the driver circuit is introduced to boost the gate of IGBT, as the gate terminal must be at least 10 volts higher than drain terminal for the IGBT to conduct. Figure 5 is the block diagram shown below.

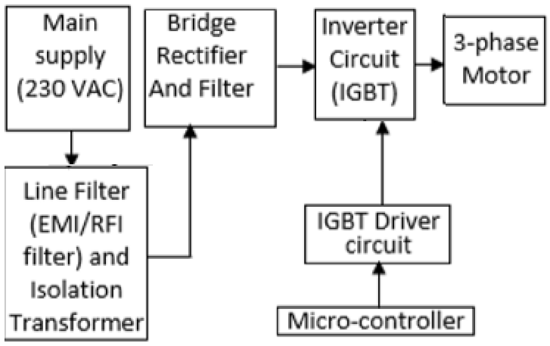

Figure 5: Block diagram

4. Pulse Width Modulation (PWM)

Inverter Pulse Width Modulation (PWM) is the process that modifies the width of the pulses in a pulse train in a direct proportion to a small control signal. For a PWM circuit, a sinusoid of desired frequency is used as a control voltage. Thus, it is possible to produce a high-power waveform. The average voltage is varied sinusoidally in a manner suitable for driving AC motors. The motor speed is fixed when the motor is connected directly to the AC line. The speed is calculated as follows:

$$n_s = 120 * f / p - slip$$

Whereas: n_s = Motor speed (Hz)
f = fundamental frequency
p = no. of poles

The fixed speed is a problem as many applications require change in speed of the motor which was traditionally achieved reducing the voltage across the windings of the motor. This in turn reduced the current through the windings thereby reducing the motor torque. If the load on the motor remains same then, the speed of the motor reduces proportionally with the voltage. But, since the load is not constant this technique is not ideal. Also, the efficiency of the motor is significantly reduced as the slip on a motor is too great. A full control over the motor is achieved via the microcontroller and IGBT pair in the inverter stage. The inverter consists of six IGBT's, two IGBT's for each motor winding. phase. The microcontroller sends gate signals and

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the IGBT's are switched on and off creating an average AC voltage close to a sinusoidal waveform. The duty cycle of the IGBT is varied which provides equivalent sine wave output. The modulation of duty cycle is phase shifted by 120 degree for each phase.

An effective control over fundamental frequency and voltage of the output is achieved. When the IGBT's are switched off, a back emf is produced in the motor winding that generates a very high and potentially damaging voltage across the IGBT.

To overcome this problem, the inverter has antiparallel diodes connected across each IGBT that will allow current flow from the motor winding to the dc link when the IGBT's are switched off. The back emf is directly proportional to the rotational velocity and opposite in polarity to the voltage applied across inverter. To drive the current through the motor windings and to increase motor speed and torque, both modulating frequency and voltage must be increased. The back emf and the motor speed are proportional to each other. Therefore, to maintain the current flow the supply voltage to the motor winding must be above this emf.

5. Advantages

As VFD usage in HVAC applications has increased, fans, pumps, air handlers, and chillers can benefit from speed control. Variable frequency drives provide the following advantages:

1) **Energy savings:** The primary function of VFD is to provide energy saving. The VFD can save the energy up to 50%.
2) **Low motor starting current:** At the time of starting the motor start with low frequency so it takes low current at starting therefore VFD can be used as starter.
3) **Reduction of thermal and mechanical stresses on motors and belts during starts:** By using VFD the thermal and mechanical stress on motors and belts during starting get reduced hence chances of wear & tear of various part get decreased.
4) **Simple installation:** As VFD is single unit and it does not required any concrete construction so its installation is simple.
5) Lower KVA As VFD has nearly unity power factor it has lower KVA rating.

6. FAN Application

In variable airflow applications, it is common to use mechanical control devices like dampers while the motor continues to run at its rated power. This mode of operation is not efficient from an energy savings point of view since the power consumed is always constant, regardless of the desired airflow. The load torque in a fan application is proportional to the square of the speed, according to Equation (2), and the power consumed is proportional to the cube of the speed

$$\mathbf{T_L=k_1n_m^2} \quad (2)$$

where k
1
is proportionality constant

For this present study, a fan curve was assumed to be k_1=8.546x10^{-8}. Figure 6 illustrates the torque-speed characteristic of the motor at different operating voltages as well as the fan load curve. The intersection points of the fan curve with each of the corresponding motor curves signify the operating points for the fan at particular speeds. Each speed produces a specific air flow.

The theoretical results presented in Table 2 show the torque, speed, corresponding slip, power consumed and generated along with the efficiency of the motor at each of the intersecting points (fan operating points) (see Figure 6). In addition, the power savings compared to the use of dampers is calculated using Equation (3) and included in Table 2.

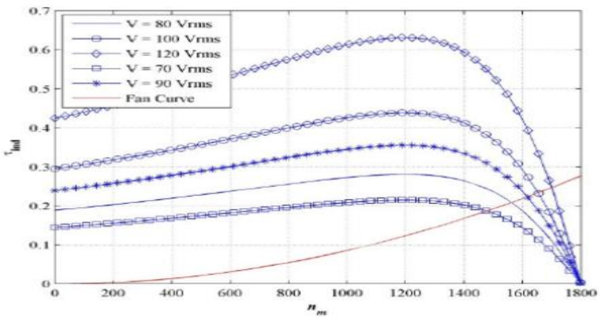

Figure 6: Variable voltage Motor characteristic and Fan Load

$$P_s = \frac{\text{Prated} - \text{Pcontrol}}{\text{Prated}} \quad (3)$$

Table 2: Operating condition for fan at different speeds due to voltage control

V (V)	T (Nm)	n_m (rpm)	S (%)	P_{in} (W)	P_{out} (W)	η (%)	Pf	P_s (%)
70	0.186	1476	0.181	0.180	28.770	50.55	0.72	32.75
80	0.209	1576.4	0.133	0.133	34.147	52.50	0.74	23.20
90	0.224	1617.1	0.102	0.102	37.146	53.06	0.72	15.75
100	0.234	1654.2	0.081	0.082	40.534	53.04	0.70	9.76
120	0.247	1700.2	0.055	0.055	44.046	52.01	0.63	0

The data presented in these tables makes it abundantly clear that operating the motor at lower speeds, when less air flow is called for by the application, yields energy savings. Notice that the torque levels at each operating point is within the 100% load range of the motor. This is the reason why the efficiency and the power factor of the motor maintain an almost constant level, with minimum differences among the operating points.

7. Conclusion

Hence, we concluded that VFDs provide the most energy efficient means of capacity control. This drive comes in a lead role for energy saving products for the all industries using electrical motors. Adding a variable frequency drive (VFD) to a motor-driven system can offer potential energy savings in a system in which the loads vary with time.

The operating speed of a motor connected to a VFD is varied by changing the frequency of the motor supply voltage. This allows continuous process speed control. Motor-driven systems are often designed to handle peak loads that have a safety factor. This often leads to energy inefficiency in systems that operate for extended periods at reduced load.

The ability to adjust motor speed enables closer matching of motor output to load and often results in energy savings. VFD can be used for the number of applications of Induction motor and speed can get control as per load requirement so energy consumption get reduced hence VFD becomes very reliable and economically beneficial.

It is worth emphasizing that while PWM methodologies are usually embedded in numerous motor drives for their positive impact on the efficiency of the drives, the overall control scheme still needs to be evaluated carefully for its overall efficiency

The fan application was studied for voltage control and variable-frequency control. These two schemes were chosen because of their higher efficiency compared to phase control. The variable-frequency drive yielded better results from an energy efficiency point of view. In addition, it is important to note that the variable-frequency drive works for a wider range of speeds, resulting in more versatility for the fan application. Thus, in some applications it might be necessary to have several options for the airflow and a wider range of speed would be needed. However, very high speeds may require changing the control scheme.

References

[1] Mohan, N., Undeland, T., and Robbins, W. (1998). Power Electronics: Converter, Applications, and Design. New York: John Willey & Sons, Inc.
[2] Hamad, S. H., Bashi, S. M., Aris, I., & Mailah, N. F. (2004). Speed Drive of Single-Phase Induction Motor. National Power & Energy Conference (PECon). Proceedings, Kuala Lumpur, Malaysia.
[3] Electrical machine design book by A.K. SAWHNEY – “design of single phase induction motor”.
[4] Power Electronics and Drives-By P.S. Bhimrah
[5] Yildirim, & Bilgic, M., (2008). PWM AC Chopper Control of Single-Phase Induction Motor for Variable-Speed Fan Application. Proceedings of Industrial Electronics, IECON 34th Annual Conference of IEEE.

Author Profile

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