# Analysis and Development of a Speed Controller for Induction Motors Using a Pulse Width Modulated AC Chopper

<sup>1</sup>J.O. Egwaile, <sup>2</sup>M.A. Oriahi, <sup>3</sup>K.O. Ogbeide

<sup>1,2,3</sup> Department of Electrical/Electronic Engineering, Faculty of Engineering, University of Benin, PMB 1154, Benin City, Edo State, Nigeria. Email: <sup>1</sup> joel.egwaile@uniben.edu; <sup>2</sup> mattheworiahi@yahoo.com; <sup>3</sup> kingsley.ogbeide@uniben.edu.

Abstract - AC motors have speed control capabilities only when operating from variable frequency sources, and speed control is achieved by varying the applied voltage and/or the frequency of its inversion. The speed of an induction motor may be varied by phase angle control of the stator voltage. The phase angle control method uses a thyristor and requires that the silicon controlled rectifier be fired only once in each half cycle of the applied voltage. It is perhaps, by far, the most cost effective method of speed control and may be used on all types of loads. However, the sudden switching part-way into the applied voltage every 1/100th of a second (for 50 Hz power), results in large amounts of electrical noise which generates winding losses as heat and interferes with electronic equipment. This paper presents a speed controller scheme that uses a pulse width modulated AC Chopper in parallel with a thyristor to provide some average level of voltage before the thyristor is fired. The firing circuit was designed and the performance analysis was carried out successfully.

## Keywords- AC chopper, Electronic Switch, Phase angle firing, Silicon controlled rectifier.

#### I. INTRODUCTION

An induction machine is an alternating current machine in which the current in the rotor winding produces torque by electromagnetic induction from the magnetic field of the stator winding. The squirrel cage type induction motor is the most commonly used of all rotating machines mainly because of its uncomplicated, rugged construction and good efficiency coupled with its low initial cost and overall maintenance costs. In addition, it is easily adapted for use in a wide variety of applications with relatively simple design changes. [1].

The power delivered to, and hence the speed of an alternating current motor can be varied by:

- i. Applying full load voltage at once or at intervals of time: Direct On Line Starting, and
- ii. Applying reduced voltage gradually until the desired voltage is achieved [2].

The conventional ON-OFF speed control method of stator voltage control suffers from various disadvantages like mechanical wear and tear, frequent down time and high maintenance costs. Most motor starters utilize thyristors, or SCRs, to control the power delivered to an induction motor. As the power changes, the speed also changes. Unlike a transistor, however, the thyristor remains conductive once switched on and cannot be switched off by the gate current until the applied voltage waveform crosses zero or is otherwise switched off by forced commutation.

Many control strategies have been developed to control the speed of an induction motor by controlling the conduction angle of a thyristor or its duty cycle for an integral number of circles of the applied waveform. In general, almost all the popular methods of controlling the conduction time of a thyrstor using electronic devices are nothing but variations of either the Phase Angle firing control (PFC) or the Pulse Width Modulation firing control (PWM). The phase angle firing control is the most popular method of speed control. It is cheap and reliable, but torque is low at reduced voltages and the motor may stall on load or not start at all. The Pulse width modulation firing control is, however, perhaps by far, the most effective method of speed control. Pulse width modulation allows us to have control over the percentage ON and OFF duty cycle of the applied voltage. It is effective and very efficient, and can be used on all types of load, but it is relatively more sophisticated and costly. With PWM, the speed control of an induction motor has been shown to be more than a match for DC drives and is being applied almost everywhere where only DC drives were previously used. [3],[4].

In [5], a phase angle delayed SCR controller for the single phase induction motor by reducing it to just its R and L elements in terms of slip and validated the design by simulation. [6] presented a paper that placed emphasis on the simulation of a PWM controlled frequency inverter for induction motor using the SCR. The simulation results show how the speed control of the induction motor can be achieved through pulse width modulation. [7] designed and simulated the firing circuit for a converter using the cosine signal control method with placing emphasis on the necessity of synchronizing the firing pulses of the thyristor. The advantage of this scheme is that the output voltage is proportional to the control voltage.

The technique presented in this paper is primarily concerned with utilizing an AC chopper to provide some average level of voltage before an SCR is fired. It is effective and efficient and can be used on all types of load. The chopper supplies the load with a threshold voltage and is shorted out as soon as the thyristor is allowed to fire. In this way, the thyristor switching voltage gradient is lowered and the transient switching electrical noise and losses are minimized considerably.

#### II. METHODOLOGY

The various sections that make up the speed controller are presented in the following subsections.

#### A. The Proposed Speed Controller Scheme

The proposed scheme is illustrated in the block diagram of Fig.1. A power transistor is connected in series with a diode to act as an AC Chopper. The Chopper is connected across an SCR to produce a mean output voltage that is proportional to the duty cycle of the switch in that period. The power transistor, usually the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) or the Insulated Gate Bipolar Transistor (IGBT), is the preferred switching device. The MOSFET unlike the IGBT, has no junctions in its main current path and voltage, rather than current, is used to control the current flowing through the channel. [8]. From the provisional waveform shown it can be seen that the larger the area under the curve, the more is the power delivered.



(a): Block diagram waveform

(b): The provisional

### Fig.1: The Proposed System Block diagram and provisional waveform.

For the full wave circuit, two inverse parallel thyristors are used while the chopper is realized as shown in Fig.2. Each thyristor or transistor conducts depending on which anode is positive with respect to the potential on its cathode when a trigger pulse arrives. [7]. The thyristors and transistor are fed through a driver amplifier and isolation transformer in order to meet the twin objectives of strengthening the firing pulses and isolating the control circuit from the power circuit. [1].



Fig.2: The Single Phase Inverter Block Diagram

#### B. Modeling the Inverter

Controlling the speed of an induction motor requires that the angle of conduction of the switching thyristor be known. We begin by deriving the model equation of an induction motor in terms of slip. After a mathematical analysis, the control parameters can be found and the speed variation/control plots could then be represented by a phase control circuit that can be implemented on a circuit board.

The current through an inductive R-L load due to an alternating voltage,  $v_s = V_{sm} \sin \omega t$  is given by the Equation

$$L\frac{d}{dt}i + Ri = V_{sm}\sin\omega t \tag{1}$$

From which we get

$$\begin{aligned} t_T &= \frac{V_{sm}}{|Z(\omega)|} \left[ \sin(\omega t - \emptyset) - \sin \emptyset \, e^{-t/(L/R)} \right]; \\ \emptyset &\leq \omega t \leq \pi \end{aligned}$$

which indicates a waveform of repeated transients,

where 
$$\emptyset = \tan^{-1}(\omega L/R)$$

$$|Z(\omega)| = \sqrt{[R^2 + (\omega L)^2]} \cdot [10]$$

As  $\omega L/R$  increases, the exponential term decays more slowly and the current equation given in (2) may be written simply as

$$i_{T} = \frac{V_{sm}}{|Z(\omega)|} [\sin(\omega t + \partial) - \sin(\partial)];$$
  

$$\Theta \le \Theta \le \omega t + \partial$$
  
where  $\partial = \emptyset(\frac{\omega L}{R}).$ 
(3)

The presence of the angle  $\partial$ , means that there is an angle of conduction for which the current is continuous and the thyristor cannot be controlled. Thus controlling the speed of an induction motor with a thyristor becomes essentially an exercise in controlling the firing phase angle of the thyristor. The relationship between  $\partial$  and  $\emptyset$  can be evaluated by plotting the curves  $\partial = ({}^{wL}/{}_R)\emptyset$  on the same graphic window for varying values of  ${}^{\omega L}/{}_R$ , as shown in the MATLAB computer simulation of Fig.3.



An electric motor takes in electrical power and delivers it at the shaft as mechanical power. The power that is read on the nameplate of a motor includes the power factor term, which mirrors the efficiency of the energy conversion. Typically, the nameplate gives the power factor of the motor for its rated power and speed at a power factor of 0.8.[9]. Using the trigonometrical identity

$$\cos^2 \emptyset + \sin^2 \emptyset = 1$$
,  
we have

$$\sin \emptyset = \frac{\omega L}{|Z(\omega)|} = 0.6$$

so that

$$\tan \phi = \omega L/R = \frac{0.6}{0.8} = 0.75,$$
  
where  
$$\cos \phi = \frac{R}{|Z(\omega)|} = 0.8$$
  
and  
$$|Z(\omega)| = \sqrt{[R^2 + (\omega L)^2]}$$

At no load, the speed is near synchronous and the power factor is near unity.  $\omega L/R$  increases the slip and the power factor falls. The difference is usually relatively small. Assuming a worst case drop of 0.75, down from 0.8,

$$\emptyset = \cos^{-1}0.75 = 41.4^{\circ}$$
,  
so that  
 $\frac{\omega L}{R} = \tan 41.4^{\circ} = 0.88$   
and

 $\partial = 30^{\circ}$ .

Then, for a test motor with nameplate data of 1.5Hp, 220 Volts, 6.25 amps and 1500 RPM at 50 Hz,

$$Z(\omega) = \frac{V_s^2}{0.75P_{in}} = 34,2\Omega$$
  
so that:  
 $R_s = 34,2\cos 41.4^\circ = 26.4\Omega$ 

and  

$$L_s = \frac{34,2}{\omega} \sin 41.4^\circ = 0,07H$$
 (6)

#### C. Modeling the AC Chopper

We synthesized the PWM to drive the chopper from the supply voltage-derived pulsating dc signal by connecting a square wave oscillator signal to the noninverting input of a comparator. The average or mean value of a sinusoidal voltage,

 $v_s$ , which is switched by a repetitive ON and OFF

square wave signal may be expressed as

$$V_{AVM} = \frac{I_{ON2}}{0.5T_1} v_s$$
(7)

where

 $T_1$  is the period of the alternating voltage,  $V_{s}$ , and

 $T_{ON2}$  is the ON pulse width of a square wave signal relative to  $T_1$ .

If we make  $T_{ON2 = m}T_2$ , where *m* is the percentage duty cycle of the square wave, then

$$V_{AVM} = \frac{mT_2}{0.5T_1} v_s = \frac{2mf_1}{f_2} v_s$$

(8)

or

$$V_{SM}|_{p.u} = k * \frac{f_1}{f_2}$$
(9)

where.

(5)

$$V_{SM}|_{p.u} = \frac{V_{AVM}}{v_s}$$

which is equal to the per unit value of AVM and k = 2m.

The MATLAB simulation of (3) for varying values of k (0 > k >1) is shown in Fig.4, which indicates that  $VSM|_{pu}$  decreases as  $f_2$  increases, relative to  $f_1$ , for a given value of k. For k = 1 (m = 0.5) and  $f_1/f_2 = 0.5$ ,  $VSM|_{pu} = 0.5$ . For k = 0.4 (m = 0.2) and  $VSM|_{pu} = 0.2$ ,  $f_1/f_2 = 0.332$ . Therefore, to drive the chopper transistor and give an average output voltage of 0.2 x 220, or 44 volts at 50 Hertz, we needed to design a square wave signal generator with a repetitive frequency of

$$f_2 = 3f_1 = 150$$
Hertz (10)

Period  $T_2 = 1/150 = 6.7$  milliseconds (11) or, 3.3ms in one half cycle of the applied voltage and

Pulse width 
$$T_{ON2} = mT_2 = 0.66$$
 milliseconds (12)



Fig.4: Plot of VSM $|_{pu}$  vs  $f_l/f_2$  for varying values of k = 2m.

#### D. Designing the square wave oscillator

A synchronized square wave may be synthesized from the input voltage synchronizing pulses by connecting a square wave oscillator as the reference input to a comparator, as illustrated in Fig.5.



Fig.5: Synchronizes Square wave generator

#### E. Designing the Phase angle delay controller

The 30 degrees conduction angle obtained in B requires that the firing pulse be delayed 3.2ms. (The period of one half cycle of a 50Hz waveform is 10milliseconds). For

 $V_{C3} \cong 0.5Vcc$ , we make t = 0.7RC, and

$$0.0032 = 0.7R8C4$$
 (13)

And if we take

C4 = 0.1 uf, we get

$$R_{\min} = 45.7 k\Omega \tag{14}$$

or the next preferred value.

And for the maximum delay conduction angle of, say 8ms (< 10 ms),

$$R_{min} = 97k\Omega$$
 (15)

We now assembled the control circuit, as shown in Fig.6, and validated the design using the PSPICE



Fig.6: Circuit simulation model of speed controller.

#### III. SIMULATION RESULT AND DISCUSSION

The modelled circuit was simulated piecemeal and the following results were obtained:

Fig.7a. shows the simulation circuit with only the chopper in operation. The result, shown in Fig.7b, indicates that the output voltage reduces to approximately 1/3, or 0.33 of the applied voltage after the third pulse, as designed. The simulation result of Fig.8 shows that the thyristor switches on at the user-defined time, thereby applying full voltage across the motor after the time delay.





(b): Simulation diagram

Fig.7: Input and Output voltage with Chopper only operating.



(b): Simulation diagram

Fig.8: Input and Output voltage with Thyristor only operating.

#### IV. CONCLUSION

This paper presents the modeling and simulation of a single phase AC voltage controller for a single-phase

induction motor. Speed control was achieved by connecting an ac chopper in parallel with a thyristor and firing both switches simultaneously. The chopper introduces a threshold operating voltage, and then, the thyristor is switched on to apply the full voltage, every half cycle of the applied voltage. In this way, the output voltage, and hence the speed of the motor, is controlled. Three phase operation is possible if each thyristor-chopper pair is placed in each leg of a three phase supply.

- G Thaler and M Wilcox "Electrical Machines", John Wiley & Sons Publishers, New York, 1966.
- [2] A Roman and A Heiligenstein "SCR Power Theory Training Manual.pdf", 2001, available on http://www.chromalox.com/ Training Manual.pdf, accessed July 2015.
- [3] T Lipo and K Jezernik "AC Motor Speed Control"available at <u>http://www.ro.feri.uni-mb.si/AC\_motor\_book</u>, 2002, sighted June 2015.
- [4] M. Barr "Introduction to Pulse Width Modulation" 2005. (http://www. Allaboutcircuits.com, Accessed 15 June, 2017.
- [5] O. Oladepo and A Adegboyega, "MATLAB Simulation of Single-Phase SCR Controller for Single Phase Induction Motor", International Journal of Electronic and Electrical Engineering. ISSN 0974-2174 Volume 5, Number 2 (2012), pp. 135-142 © International Research Publication House <u>http://www.irphouse.com</u>.
- [6] X Lu, S. Chen, C Wu and M Li "The Pulse Width Modulation and its use in induction motor speed control" IEEE Journal, Fourth International Symposium on Computational Intelligence and Design, 2011.
- [7] S Tirtharaj, K. B. Pijush K and B Manjima "Design and Implementation of Firing Circuit for Single Phase Converter", International Journal of Computer and Electrical Engineering, Vol. 3, No. 3, June.
- [8] I, Sinclair "Practical Electronics Handbook" by Newnes Technical Books. Buttenworth & Co Publishers. 1980.
- [9] Http://www.machinedesign.com/motorsdrives/basics-motornameplates
- [10] J. Watson, Semiconductor circuit design, The Institute of Physics, Adam Hilger Publishers Ltd, Bristol, 1976