Journal of Electrical Engineering
The Institution of Engineers, Bangladesh
Vol. EE 31, No. I & II, December 2004

Close-loop Control System of a Three-phase Induction Motor using Fuzzy Approach

Md. Nurul Islam and M. Bashir Uddin

Department of Electrical and Electronic Engineering
Dhaka University of Engineering and Technology, Gazipur, Bangladesh
E-mail: nislam_03@yahoo.com

ABSTRACT

In this paper, it is proposed to control the speed of a three-phase induction motor by microcomputer with flux control. To estimate flux, the system needs to sample line current and speed and solve first order simultaneous differential equations. But complications arise with the numerical solution of differential equations. Also uniform and periodic sampling technique necessary to solve differential equation is complicated due to hardware limitation. Hence Fuzzy-mapping technique is proposed to make computation efficient in real time system. Triangular modulation of the inverter is used in control system. But the software to implement triangular modulation on the basis of comparison of carrier wave with modulating signal has many limitations. A new simplified analytical equation formulated based on certain approximations without loss of accuracy is used to determine the switching points of a three-phase inverter.

1. INTRODUCTION

The control and estimation of ac drives in general are considerably more complex than those of dc drives. Most of the induction motor drives are based on keeping constant voltage/frequency (V/f) ratio in order to maintain a constant flux in the machine. Although the control of V/f drives is relatively simple, the torque and flux dynamic performance is extremely poor [1]. A speed control with close-loop flux control improves performance of the motor under volts/Hz control and eliminates the flux drift due to line voltage variation. The flux feedback signals are estimated from machine terminal quantities on rotor field orientation.

Modulation of static converter waveform is common method of simultaneous voltage and frequency control. Sine pulse width modulation is the most common technique for obtaining switching points of inverter. The sine modulating wave is compared with a triangular wave and the points of intersections of these two waves determine the switching points of an inverter. Software implementation of this algorithm has many limitations. The foremost of them is high frequency switching. The proposed modulation technique is based on simplified analytical equations with certain approximations [2].

Here rotor flux and speed are used as control parameters. To estimate flux, the system needs to sample line currents and speed and solve first order differential equations. But numerical solution of differential equations is not efficient. The time derivative of a signal from sampled measurements is corrupted by noise [3]. The main complication is that differentiators amplify high frequency noise. This problem grows with the order of the derivative. Another necessary condition to solve differential equation numerically is periodic sampling. Using PLC 812PG data acquisition card line current and speed are sensed. But periodic sampling is complicated in real system. Also the application of periodic sampling does not suffice. Studies have indicated that randomness in sampling is not always harmful. These nonuniform sampling provide useful effect as the suppression of aliasing. This nonuniform sampling technique is applied here.

In this paper, a simple but efficient technique of fuzzy mapping is proposed replacing the differentiation in flux estimation and making the overall control system efficient. This is a simple way to arrive at a definite conclusion based problems mimics how a person would make decisions, only much faster.

2. CONTROL SYSTEM

2.1 The Proposed Control System

The close-loop control is normally required to satisfy the steady state and transient performance specifications of ac drives. In closed loop speed control, the speed loop error signal controls the PWM inverter frequency and voltage. The voltage of the machine is controlled to control the flux and frequency or slip is to control the speed.

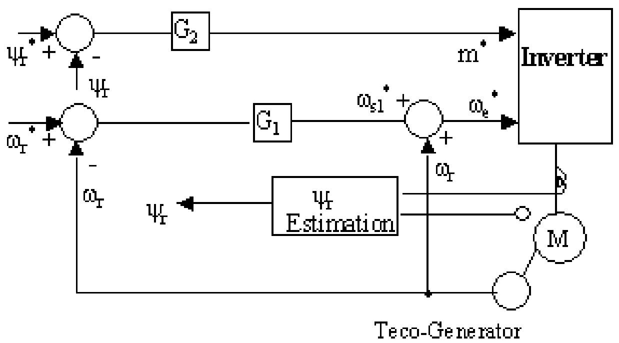

Fig. 1: Block diagram of control system.

The machine's dynamic model referred to stationary reference frame and represented by following equation is nonlinear and multivariable.

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + PL_s & 0 & PL_m & 0 \\ 0 & R_s + PL_s & 0 & PL_m \\ PL_m & \omega_r L_m & R_r + PL_r & \omega_r L_r \\ -\omega_r L_m & PL_m & -\omega_r L_r & R_r + PL_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{1}$$

where $P = \dfrac{d}{dt}$.

Then rotor loop equations can be written as

$$0 = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} + \omega_r \Psi_{qr} \tag{2}$$

$$0 = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} - \omega_r \Psi_{dr} \,. \tag{3}$$

The value of i_{dr} and i_{qr} can be written as

$$i_{dr} = \frac{\Psi_{dr}}{L_r} + (\sigma - 1)\frac{L_s}{L_m} i_{ds} \,, \tag{4}$$

$$i_{qr} = \frac{\Psi_{dr}}{L_r} + (\sigma - 1)\frac{L_s}{L_m} i_{qs} \,. \tag{5}$$

Where $\sigma = \dfrac{L_s L_r - L_m^{\ 2}}{L_s L_r}$.

Now substituting the values of i_{dr} and i_{qr} in rotor loop equations

$$\dot{\Psi}_{dr} = \frac{R_r}{L_r}(L_m i_{ds} - \Psi_{dr}) - \omega_r \Psi_{qr} \,, \tag{6}$$

$$\dot{\Psi}_{qr} = \frac{R_r}{L_r}(L_m i_{qs} - \Psi_{qr}) + \omega_r \Psi_{dr} \,. \tag{7}$$

So rotor flux,

$$\psi_r = \sqrt{\left(\psi_{dr}^{\ 2} + \psi_{qr}^{\ 2}\right)} \,. \tag{8}$$

In the case of a cage induction motor, the rotor flux can be determined analytically via stator voltage integration. However, due to the stator resistance voltage drop, the result may be biased. This could affect the performance of the drive at low speed. To overcome this drawback, the rotor flux must then be estimated using a state observer Eqs. (6) and (7). The estimation of the rotor flux using a state observer involves the rotor resistance, which is known to vary with frequency and temperature [4]. This parameter must then be jointly estimated with the rotor flux components, and its actual value must be fed forward to the speed, flux and torque controllers to make them robust.

2.2 Modulation Technique

The software to implement triangular modulation on the basis of comparison of carrier wave with modulating signal has so many limitations. A new method using simplified analytical equations based on certain approximations are used to determine the switching points of a three-phase inverter [2]. The method of determining switching points for a typical triangular sine pulse width modulation is described with the help of Fig.2.

Here θ_i is the mid-point of the i-th pulse, x_1 and x_2 are the switching points. It can be expressed as

$$\theta_i = \frac{2i - 1}{N}\pi \,, \tag{9}$$

where $N = \dfrac{f_c}{f_m}$,

f_c = frequency of modulating wave,
f_m = frequency of carrier wave.

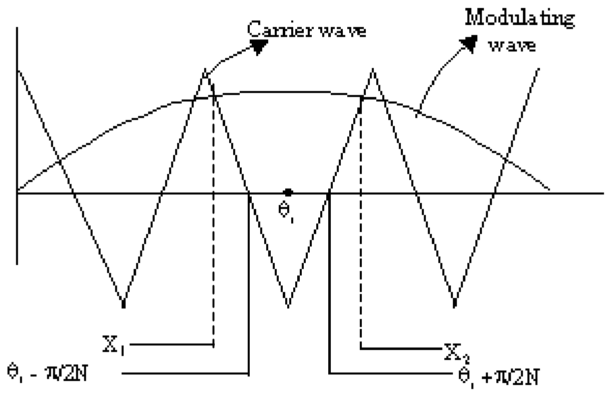

Fig. 2: Determination of switching points.

Width of the *i*-th pulse,

$$\delta_i = x_2 - x_1 = \frac{\pi}{N}(1 + m\sin\theta_i)\,. \tag{10}$$

Then switching points can be presented as,

$$x_1 = \theta_i - \frac{\delta_i}{2}\,, \tag{11}$$

$$x_2 = \theta_i + \frac{\delta_i}{2}\,. \tag{12}$$

The switching points obtained by the proposed simplified Eqs. (11) and (12) are compared with that obtained by conventional comparison method of intersection between modulating wave and triangular wave. A modulating signal of 50 Hz, carrier wave 250 Hz and modulation index of 0.8 are used for comparison. The small difference found from comparison of the results shown in Table 1 has insignificant effect on fundamental voltage of the inverter.

Table 1: Comparison of switching points.

Proposed method (sec.)	**Conventional method** (sec.)
0.0000	0.0016
0.0042	0.0048
0.0078	0.0052
0.0090	0.0084
0.0110	0.0100
0.0138	0.0116
0.0142	0.0148
0.0175	0.0152
0.0185	0.0184
0.0200	0.0200

2.3 Fuzzy Mapping Technique

Fuzzy Logic offers several unique features that make it a particularly good choice for many control problems. It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or destroyed. The output control is a smooth control function despite a wide range of input variations [5,6]. It can control nonlinear systems that would be difficult to model mathematically. Fuzzy Logic incorporates a simple, rule-based IF X AND Y THEN Z approach to a solving control problem rather than attempting to model a system mathematically. It requires some numerical parameters like error signal and/or significant rate of change of error signal, but exact values of these numbers are usually not required.

From the block diagram the system needs to estimate rotor speed and flux. The control system always tries to maintain the command value of flux and speed. To estimate flux, the system needs to sample line currents and speed to solve two first order simultaneous differential Eqs. (5) and (6). To solve the differential equations the instantaneous value of line current must be sampled in equal time interval. In a real time system it is almost impossible due to hardware and software limitations. Moreover, some signals will have discontinuities and/or ripple that would result in spikes when differentiated. In most cases the problem of the impact of the measurement errors on numerical evaluation of differential operators is insurmountable [7]. So an alternate method needs to be used. Here fuzzy mapping approach is proposed to solve the problem. In the block diagram of control system, it needs to map speed with frequency and flux with modulation index.

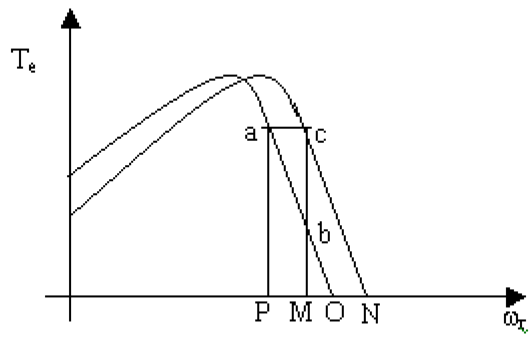

Fig. 3: Characteristic curves of an induction motor.

To relate frequency with speed, the torque-slip curves of an induction motor shown in Fig.3 can be used. Let the motor is operating at point ‘b’. Due to applied load the speed will tend to drop corresponding to point ‘a’. However, the speed loop will increase the frequency until the original speed is restored at point ‘c’. It can be demonstrated from the Fig.3 that MP = ON. Hence there is a linear relation between speed change and frequency change.

Using Eqs. (5) and (6), the rotor flux can be calculated from direct axis and quadrature axis component of line current. It is found that there is a proportional relation between line current and rotor flux up to a certain limit Fig.4.

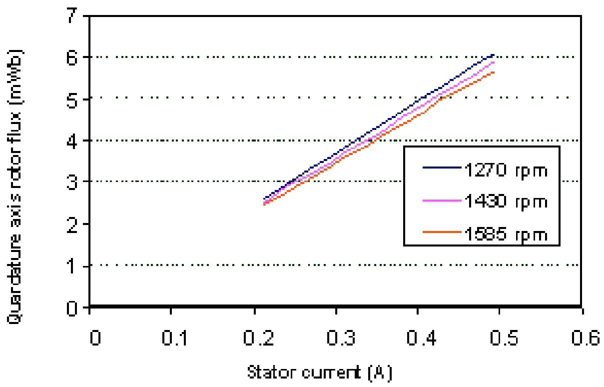

Fig. 4: Relation between flux and current.

Again to generate the control signals we need to map the change of speed with the change of frequency and the change of flux to the change of modulation index. So the full control system needs huge calculation, which is not preferable for real time system. To solve this problem a fuzzy mapping is used which can directly map the change of speed to the change of frequency and the change of line current to the change of modulation index. To do this at first line current, line voltage and speed of the induction motor are measured at variable frequency and modulation index at no-load condition (Table 2 in appendix). From the data in Table 2, effect of line current variation for variation of modulation index and effect of speed variation for variation of frequency are shown in Table 3 and Table 4 respectively and mapping between modulation index and line current, frequency and speed are constructed and shown in Fig.5 and Fig.6, respectively. It is found that the mapping is almost linear.

Table 3: Effect on line current variation for variation of modulation index.

m_{diff}	i_{diff} (rms)	i_{diff} (peak)
-0.10	-0.0266	-0.0376
-0.05	-0.0136	-0.0192
0.00	0.0000	0.0000
0.05	0.0122	0.0172
0.10	0.0234	0.0330

Table 4: Effect on speed variation for variation of frequency.

f_{diff}	N_{diff}
-5	-156
-2	-61
0*	0
2	64
5	159

* center frequency is 50 Hz.

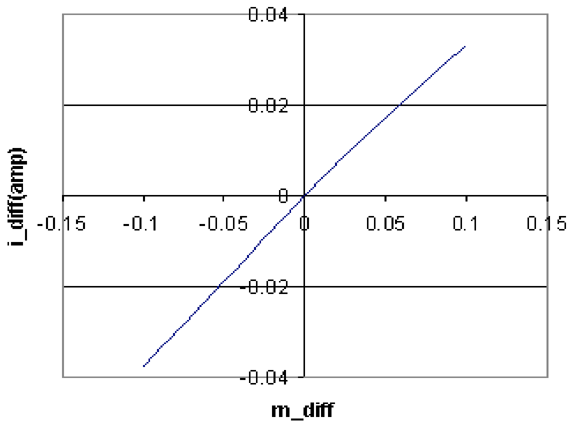

Fig. 5: m_{diff} vs i_{diff} curve.

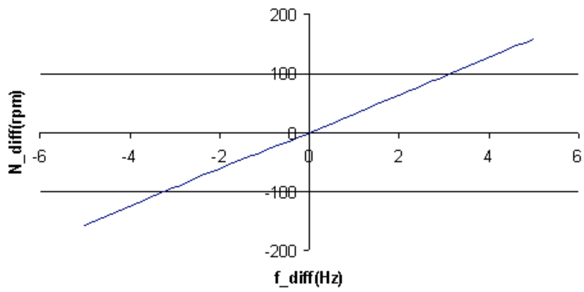

Fig. 6: f_{diff} vs N_{diff} curve.

The proposed closed loop control system samples the rotor speed and peak value of line current. It tries to keep the rotor speed and line current at their command value independently. Here the command line current and rotor speed are considered 0.38 Amp (peak) and 1450 rpm respectively. When the speed or line current is deviated from its rated value, the system first calculates the change of control variables and finds the output frequency and modulation index from the Fig.5 and Fig.6, respectively.

3. EXPERIMENTAL RESULTS

In this experiment a 3-phase induction motor with $R_s = 9.5\ \Omega$, $R_r = 10.09\ \Omega$, $L_s = L_r = 1.25$ H, $L_m = 0.446$ H has been used.

The wave shapes of phase voltage, line voltage and line current are shown in Fig.7.These wave shapes demonstrate that the proposed triangular modulation technique reduces the distortion factor and it requires small filter to smooth wave shapes.

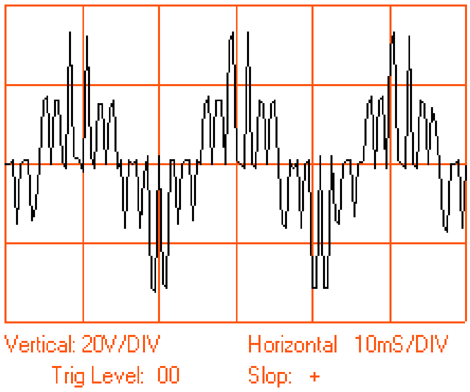

Fig. 7(a): Wave shape of phase voltage.

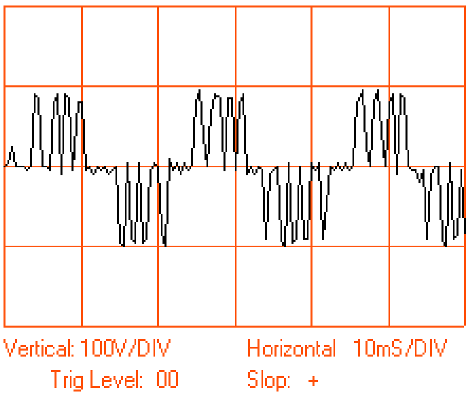

Fig. 7(b): Wave shape of line voltage.

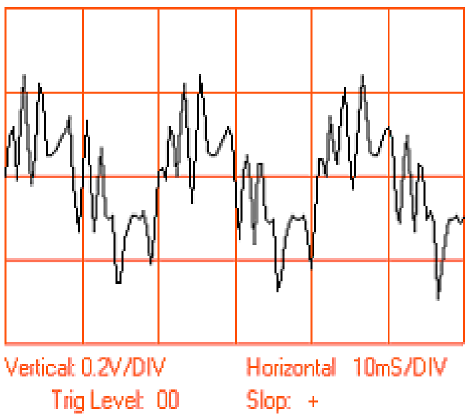

Fig. 7(c): Wave shape of line current.

The control system has been tested for three loaded conditions and the controlling process has been observed. The steps are shown in Table 5 to Table 7.

Table 5: Induction motor with first loaded condition.

Frequency (Hz)	**Modulation Index** (m)	**Peak Line current** (A)	**Speed**
50	0.8	0.396	1382
52	0.82	0.393	1446

Table 6: IM with second loaded condition.

Frequency (Hz)	**Modulation Index** (m)	**Peak Line current** (A)	**Speed**
50	0.8	0.361	1400
52	0.85	0.374	1460

Table 7: IM with third loaded condition.

Frequency (Hz)	**Modulation Index** (m)	**Peak Line current** (A)	**Speed**
50	0.8	0.445	1375
54	0.7	0.4.9	1448

4. CONCLUSION

A new simple control strategy for the three-phase induction motor has been presented. A new switching technique of three-phase inverter is also implemented based on algebric equations rather than natural intersections between carrier wave and modulating wave. The control system requires sampling line current, speed and estimation of flux. But on-line solution of differential equation to estimate flux is not optimistic. Hence fuzzy mapping is proposed to simplify the overall control strategy as it is inherently robust and immune to noise inputs and output control is smooth despite a wide range of input variations.

REFERENCES

[1] Bimal K. Bose, *Modern Power Electronics and AC Drives,* Prentice Hall, 2002.

[2] M. Bashir Uddin, "Stability Analysis of PWM Inverter-Fed Synchronous Motors," P.hd. Thesis, BUET, January, 1996.

[3] Aleksander Ignjatovic, *Numerical Differentiation And Signal Processing*, Kromos Technology Inc., Los Altos, CA 94022, July 2, 2001.

[4] Coline Grantham and Douglas J. McKinnon, "Rapid Parameter Determination for Induction Motor analysis and Control," *IEEE trans. on industry applications*, vol. 39 , no. 4, July-August, 2003.

[5] Steven D. Kaehler, (2004, July 11) Fuzzy Logic - An Introduction.[Online]. Available: http://www. seattlerobotics.org/encoder/mar98/fuz/fl_part1.htm1.

[6] Dr. Stefan Beierke, "Enhanced Control of an Alternating Current Motor Using Fuzzy Logic and a TMS320 Digital Signal Processor," Texas Instruments, March, 1996.

[7] Bengt Carlsson, Anders Ahlen, "Optimal differential Based on Stochastic Signal Models," *IEEE Trans. on Signal Processing*, vol. 39, no. 2, February, 1991.

APPENDIX

Table 2: Output voltage, line current and speed of the three-phase induction motor at variable frequency and modulation index at no-load condition.

f (Hz)	m	$V_{a(rms)}$(volts)	$i_{a(rms)}$(Amp)	$i_{(rms)}$(Amp) (Diff)	N (rpm)	N(Avg)
45	0.70	39.1	0.300	-0.028	1266	1270
	0.75	42.4	0.314	-0.014	1269	
	0.80	44.5	0.328	0*	1270	
	0.85	47.7	0.342	0.014	1271	
	0.88	49.6	0.352	0.024	1271	
48	0.70	38.6	0.279	-0.028	1364	1365
	0.75	41.7	0.290	-0.017	1364	
	0.80	44.4	0.307	0*	1365	
	0.85	47.1	0.319	0.012	1365	
	0.90	50.4	0.331	0.024	1366	
50	0.70	39.0	0.270	-0.028	1424	1426
	0.75	42.0	0.287	-0.011	1424	
	0.80	44.6	0.298	0*	1426	
	0.85	47.4	0.309	0.011	1428	
	0.90	50.6	0.320	0.022	1428	
52	0.70	38.4	0.258	-0.028	1488	1490
	0.75	41.4	0.271	-0.015	1489	
	0.80	44.2	0.286	0*	1491	
	0.85	47.2	0.299	0.013	1492	
	0.9	50.4	0.307	0.021	1492	
55	0.72	39.5	0.249	-0.020	1582	1585
	0.75	41.4	0.258	-0.011	1582	
	0.80	44.3	0.269	0*	1584	
	0.85	47.4	0.280	0.011	1586	
	0.90	50.2	0.295	0.026	1588	

*Taking central modulation index at 0.8
f = frequency, m = modulation index