Speed control of 3-phase induction motor using rotor impedance

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Abstract. This paper introduces a method of rotor impedance control by using controlled capacitor/inductor connected in series in the rotor circuit. The proposed system can be operate as a speed control system or a soft starting system to limit the starting current of the motor. An approach to a three MOSFETs-based a rotor circuit of induction motor is presented. The experimental realization of the drive posed some serious problems, notably with regard to the successful driving pulses of MOSFETs over a wide speed range. Analysis of the secondary MOSFETs-controlled motor raised many interesting challenges. It was decided to use an equivalent circuit approach to the analysis because the primary voltage and current were both largely sinusoidal. The equivalent circuit used is based on the single-phase equivalent of a balanced sinusoidal three-phase system. The effective value of the external rotor inductance or capacitance is calculated. Moreover, the motor performance specially speed, motor starting current, and torque during the control of duty cycle of MOSFETs are studied. Also, MOSFETs performance has been studied. Closed loop speed control of the motor speed have been investigated using hysteresis control based on controlling MOSFETs duty cycle. Experimental results have been carried out in the Laboratory to verifying the analysis. The simulation results are given and proved to yield good agreement when compared with the experimental results.

Keywords: Microprocessor, Mosfets, Induction Motor, and Rotor Impedance Control

1. Introduction

The induction machine is a rugged, reliable and less expensive ac machine. It has been used for high performance drive applications. Different control methods of varying degrees of complexity have been proposed and used for the control of induction machines [I, 10, 11, 12, 13, 14].

Stator voltage control of three-phase induction motor is a popular scheme used in industry for torque and speed control. A common method of controlling the stator voltage is by use phase angle control of thyristor circuit inserted in series between the supply and motor. Other methods use AC chopper with pulse width modulation PWM technique to control the applied voltage of the motor [2-4]. Method of the motor control based on the rotor circuit is used, such as using a thyristor-controlled resistive network in each rotor circuit [5-6]. This method will increase the rotor losses (heating). Operating the motor close to its rotor resonance by using reactive circuits in the rotor [7] gives high starting and breaking torque. This technique is limited as the rotor resonance is related to the varying motor speed. This paper introduces a method of rotor impedance control. By using controlled
capacitor/inductor connected in series in the rotor circuit. The proposed system can be operated as a speed control system or a soft starting system to limit the starting current of the motor.

2. System description
A schematic diagram of the proposed system is shown in Figure 1. It is composed of a power electronic converter of three switching legs and the controller. Each converter leg consists of one MOSFET transistor, and a single-phase diode bridge. A three-phase stator windings of the slip-ring induction motor is connected directly to a three-phase sinusoidal a-c supply. On the other hand, the rotor windings are connected to three-phase R or R-L or RC load in parallel with the three switching legs. The equivalent circuit of the induction motor (rotor side) with the series element is shown in Figure 2. The speed controller receives the error signal between the preset speed (reference speed) and the actual measured speed of the motor shaft, then transfers it to the microprocessor through an Analog/Digital (ND) converter. The controller is interfaced to the power converter through a three-channel gate drive circuit. Each channel consists, as shown in Figure 3, of an optocoupler isolator and open buffer gates to deliver the control signals to the MOSFET. The input signals to the gate drive circuit are obtained from the microprocessor output port to give the speed control action according to the input error signal. An assembly program is designed and written for the microprocessor to apply the hysteresis method and the ON/OFF control. The microprocessor controls the switching process according to the following conditions:

If error signal > zero, the MOSFETs are ON
If error signal ≤ zero, the MOSFETs are OFF

3. Motor mathematical model
The following main assumptions are taken into consideration:
The space harmonic, saturation effects, and iron losses are neglected. Also, the r.m.f. is sinusoidal distributed. The voltage balance equations for a three-phase motor are [8]:

\[ e_{sa} = \rho \psi_{sa} + r_s i_{sa} \]
\[ e_{sb} = \rho \psi_{sb} + r_s i_{sb} \]
\[ e_{sc} = \rho \psi_{sc} + r_s i_{sc} \]
\[ e_{ra} = \rho \psi_{ra} + r_r i_{ra} \]
\[ e_{rb} = \rho \psi_{rb} + r_r i_{rb} \]
\[ e_{rc} = \rho \psi_{rc} + r_r i_{rc} \]

In matrix notation, the relation between the phase flux linkages and the phase currents may be expressed as:

\[ \psi = [L] i \]  (3)

Where

\[ \psi = [\psi_{sa} \ \psi_{sb} \ \psi_{sc} \ \psi_{ra} \ \psi_{rb} \ \psi_{rc}]^T \]  (4)

and \[ i=[i_{sa} \ i_{sb} \ i_{sc} \ i_{ra} \ i_{rb} \ i_{rc}]^T \]  (5)

and \[ [L] = \begin{bmatrix} L & L & L \\ L & L & L \end{bmatrix} \]  (6)

Where
\[ L_{11} = \begin{bmatrix} L & L_s & L_s \\ L_s & L & L_s \\ L_s & L_s & L \end{bmatrix} \]

\[ L_{12} = \begin{bmatrix} M \cdot c \cdot \theta & M \cdot c \cdot (\theta + \frac{2}{3}) & M \cdot c \cdot (\theta - \frac{2}{3}) \\ M \cdot c \cdot (\theta - \frac{2}{3}) & M \cdot c \cdot \theta & M \cdot c \cdot (\theta + \frac{2}{3}) \\ M \cdot c \cdot (\theta + \frac{2}{3}) & M \cdot c \cdot (\theta - \frac{2}{3}) & M \cdot c \cdot \theta \end{bmatrix} \]

\[ L_{21} = \begin{bmatrix} M \cdot c \cdot \theta & M \cdot c \cdot (\theta - \frac{2}{3}) & M \cdot c \cdot (\theta + \frac{2}{3}) \\ M \cdot c \cdot (\theta + \frac{2}{3}) & M \cdot c \cdot \theta & M \cdot c \cdot (\theta - \frac{2}{3}) \\ M \cdot c \cdot (\theta - \frac{2}{3}) & M \cdot c \cdot (\theta + \frac{2}{3}) & M \cdot c \cdot \theta \end{bmatrix} \]

\[ L_{22} = \begin{bmatrix} L & L_1 & L \\ L_1 & L & L_1 \\ L_1 & L_1 & L \end{bmatrix} \]

Instantaneous torque and speed equations are given by

\[ T_e = \left[ (i_{sa} i_{sa} + i_{sb} i_{sb} + i_{sc} i_{sc}) \sin \theta + (i_{sa} i_{rb} + i_{sb} i_{rc} + i_{sc} i_{ra}) \sin (\theta + \frac{2\pi}{3}) + (i_{sa} i_{rc} + i_{sb} i_{ra} + i_{sc} i_{rb}) \sin (\theta - \frac{2\pi}{3}) \right] \]

and the mechanical torque equation of the motor and load is given by:

\[ J \frac{d^2 \theta_m}{dt^2} + K \frac{d\theta_m}{dt} + T_m - T_e \]  

\[ \theta = \frac{P}{2} \theta_m \]  

In solving the above differential equations, the Runge-Kutta method has been employed.

4. Microprocessor-based controller

A microprocessor-based controller [9] is a microprocessor based controller (MCU). Its detailed circuit schematics is shown in Figure 4.
Figure 1. A proposed system

Figure 2. Induction Motor (rotor side) equivalent

Figure 3. Driver circuit for one Mosfet circuit with the series element

It consists of central processing unit (CPU), which includes the 80386 microprocessor, 80387
numerical data processor (co-processor), 256K dual-port RAM, 256K EPROM, 8254 programmable interval timer iPIT), and 8259 programmable interrupt controller (PIC). The other is named input/output (I/O) unit which may include programmable digital I/O controller, programmable duty-cycle controller, AID, D A, etc. In the proposed system, the analog error signal between the reference motor speed and actual motor speed is transferred to digital value through AD channel I, and store the value in a memory location of RAM. The comparator is used to compare the error signal with the zero according to hysteresis control technique, then generates three pulses from output port to be delivered to the gates of MOSFETs through driving circuits. A system controller, which resides on a 32-bit microprocessor, provides task coordination, external interfaces, motion profile control, parameter tuning, and signal recording, and can also be used to monitor the operational status of individual processors.

![Diagram of a Microprocessor based controller module](image)

Figure 4. A Microprocessor based controller module

5. System modelling and modes of operation
There are two modes of operation, one of them occurs when Mosfets are turned-on and the other mode occurs at Mosfets are turned-off as follows:

5.1. Mosfets are turned-on
When series R or R-L or R-C is disconnect to rotor impedance. The solution of equations from I to 9 is obtained numerically using Rung-Kutta fourth-order numerical integration method.

5.2. Mosfets are turned-off
Series R or R-L or R-C is connect to rotor impedance and hence some equations 1-9 are modified in order to study motor performance at this mode of operation.

At R-series only is connected to each rotor phase, Eqn.2 is modified by replacing R+ r r instead of r r. But if R-L series is connected to each rotor phase, motor Eqns. are modified as following:

\[
L_{rr} + L_{an} + R + r = \text{Lrr and } r \text{ respectively. When R-C is connected in series with each rotor phase, } R+r, \text{ instead of } r, \text{ and added the following Eqns.}
\]

\[
dVca dt = \frac{ira}{IC}
\]
\[
dVcb dt = \frac{irb}{IC}
\]
\[
dVcc dt = \frac{irc}{IC}
\]
and modify eqs. era, erb, erc to become as following:

\[
er_a = \rho \psi \cdot r_a + (R+r_r) \cdot Ira + Vca
\]
\[
er_b = \rho \psi \cdot r_b + (R+r_r) \cdot Irb + Vcb
\]
\[
er_c = \rho \psi \cdot r_c + (R+r_r) \cdot Irc + Vcc
\]
6. Simulation results

The proposed system is designed and built in the laboratory to verify the analysis. It consists of a slip-ring induction motor. The motor parameters and data are listed in tables 1, 2

**Table 1. Data of induction motor**

| Name plate data     | Value          |
|---------------------|----------------|
| Input Voltage       | 220 Volt.      |
| Frequency           | 50 Hz.         |
| Motor Connected     | 3-phase star   |
| No. of Poles        | 4 poles        |
| Output Power        | 0.75 HP        |
| Rated speed         | 1450 r.p.m.    |
| Rated Current       | 1.2 Amp.       |

**Table 2. Nominal parameters of induction motor**

| Nominal parameters | Value           |
|--------------------|-----------------|
| Lss                | 0.4671 H        |
| Lrr                | 0.4671 H        |
| Lsm                | 0.23155 H       |
| Lrm                | 0.23155 H       |
| Msr                | 0.42887 H       |
| R1                 | 19 ohm          |
| R2                 | 10 ohm          |
| K                  | 0.0001 Kg. m²/s |
| J                  | 0.004 Kg.m²     |

Series R, L and C connected to rotor phase are 420hm, 0.2H and 50 pf respectively. The hardware setup consists of a microcomputer based on microprocessor 80386, 12-bits A/D card, 12-bits D/A card, three MOSFETs with type IRFP740, three uncontrolled single-phase bridges, and three R-C circuits. The microprocessor-based control system designed for the proposed system is shown in Fig.1, the control algorithm is implemented on an EPROM interfaced to the CPU of a microcomputer. The proposed control scheme was executed every 0.5 m.sec The error signal between command speed and actual motor speed is transferred through 12-bit A/D converter, the generated pulses to MOSFETs are processed from output port depending upon the error signal and hysteresis control. To check the validity of the model described above; a set of simulation tests have been carried out to analyse the system under steady state and transient conditions using C Program designed by the authors to solve the given non-linear differential Equations. Experiment is carried out to determine the characteristics of the proposed system. First, Open loop speed control of three-phase induction using controlled series impedance connected with the rotor circuit has been studied. Switch on and off of the three MOSFETs in rotor circuits can control the motor speed. The different duty ratios ton / T are selected, Where ton is turn on of the Mosfet and T is the total turn on and turn off of the Mosfet. As a practical example, 20 period (T) have been selected every one cycle of input supply frequency (50 Hz.), so each period of T equals I m.sec. Figure (5) shows the computed and experimental three-phase steady-state rotor currents at duty ratio = 20 and 50 of controlled only resistance respectively. It should be noted that fluctuating of the rotor currents is appeared due to control of adding and shorting series resistance in rotor circuit. Figure 6 shows the computed and experimental three-phase steady-state rotor currents at duty ratio = 20 and 50 of controlled resistance and inductance (R-L) respectively. It can be noted that the distortion of the rotor currents, this because of connecting and shorting the series R-L with rotor impedance in very short time 0.2 m.sec and 0.5 m.sec. Control of resistance in series with the rotor will
increase the rotor losses. Controlled R-L in rotor circuit causes the starting torque of the motor decreased whatever it gives nearly sinusoidal supply and rotor currents, for these reasons the controlled capacitance in the rotor circuit is used. So, We have replaced R-L by resistance and capacitor (R-C) series tell rotor circuit, rotor currents are obtained in Figure 7 computational and experimental. It can be concluded that the computed results are in good correlation with the results obtained experimentally. Figure 8 shows Mosfet terminal voltage and current during open loop when add or short R-L and R-C to rotor circuit with different duty ratios. Figure 9 shows the computed and experimental steady-state results of three-phase stator voltage and current at different duty cycle control of series R-C connected to rotor circuit. Spectrums of both supply voltage and current waveforms confirm the computational results. Closed loop speed control of motor has been studied experimental and computational, by connecting ON or OFF R-C series with rotor circuit depending upon the error between Reference speed and feed back motor speed taken from a Tacho-generator. As shown in Figures 10-11, Simulation and Experimental of motor performance (speed, stator current and rotor current), pulses to mosfet during step change in load torque by 20 of its rated. It can be cleared that the controller used is effective and faster. Figures 12-13 show another study of motor performance (speed, stator current and rotor current), pulses of Mosfet at a certain operating case when a reference speed is changed from 1000 r.p.m. to 800 r.p.m. suddenly and set at this value for 200 m.sec. then return back to its original steady state speed value. Controller used here is fast and accurate for (nearby 160 m.sec for reach required reference speed). Figure 14 shows simulation study of transient rotor speed at different duty cycle of R-C series controlled in rotor circuit. On the other hand, an experimental start-up of rotor speed at duty cycle = 20 of R-C series in rotor circuit is shown in Figure 15. It can be concluded that, increasing duty ratio of R-C series in rotor circuit non-linear proportionally with rotor speed and raising time is the best when using duty ratio \( \leq 100\% \).

7. Conclusion

Series controlled conservative element in the rotor circuit of the induction motor will control the rotor equivalent circuit impedance. The proposed control technique used to limit the motor starting current. In steady state operation the proposed system can be operate as speed control system. Hysteresis control (ON/OFF) algorithm is used to control operation of the switches to control the effective rotor impedance value. The computed results, which are obtained from the simulation results, are proved to yield good agreement with the relevant experimental results.

8. Appendix

a,b,c: First, second, and third phases of three-phase system
C: Series Capacitance in rotor circuit per phase.
Dl,G I,SI: Drain, gate and source of MOSFET 1 D2,G2,S2: Drain, gate and source of MOSFET 2 D3,G3,S3: Drain, gate and source of MOSFET 3
K: viscous friction constant, seconds.
i: Instantaneous current
J: Inertia of motor and connected load
L: Series inductance in rotor circuit per phase.
Lss, Lrr: Self-inductances of three-phase stator and rotor circuits, respectively.
Lsm: Mutual inductance between stator phases Lrm: Mutual inductance between rotor phases
Msr: Mutual inductance between three-phase stator and rotor circuits
p: Differential operator, d/dt
P: Number of poles
R: Series resistance in rotor circuit per phase.
s, r: Suffixed denoting stator and rotor, respectively
r: Resistance
s: Instantaneous flux linkage
O: Electrical angle denoting instantaneous rotor position, radians
Omf: Mechanical angle denoting instantaneous rotor position, radians
Te: Electrically developed torque
T, Tm: Superscript-denoting transpose of matrix and External load torque respectively
Simulation results

Figure 5. R-control of rotor resistance with different duty cycle ratios

Figure 6. R-L control of rotor resistance with different duty cycle ratios
Simulation results

Figure 7. R-C control of rotor resistance with different duty cycle ratios

(a) Rotor currents at duty ratio = 20%
(b) Rotor currents at duty ratio = 50%

(c) Three-phase rotor currents and MOSFET pulses of one phase at duty ratio = 20%
(d) Three-phase rotor currents and MOSFET pulses of one phase at duty ratio = 50%

Experimental results

Figure 8. MOSFET performance at R-L and R-C control of rotor impedance

(a) MOSFET voltage and current at duty ratio=20% (R-L Control)
(b) MOSFET voltage and current at duty ratio=50% (R-L Control)
(c) MOSFET voltage and current at duty ratio=20% (R-C Control)
(d) MOSFET voltage and current at duty ratio=50% (R-C Control)
Supply voltage and supply current (is, I amp. = 50 div.) at duty ratio = 20%

Supply voltage, stator current and MOSFET pulses at duty ratio = 20%

Supply voltage and supply current (is, I amp. = 50 div.) at duty ratio = 50%

Supply voltage, stator current and MOSFET pulses at duty ratio = 50%

Figure 9. Supply voltage and stator current at different duty ratio R-C control of rotor impedance

Figure 10. Motor performance and MOSFET pulses during step change in load torque by 20% (Simulation results)
Figure 11. Motor speed and MOSFET pulses during step change in load torque by 20% (Experimental results)

Figure 12. Motor performance during step change in reference speed (closed loop control) from 1000 to 800 r.p.m, Then return back to 1000 r.p.m,
Figure 13. Motor speed and MOSFET pulses during step change in reference speed (Experimental results)

Figure 14. Motor start-up performance at different duty ratio R-C control of rotor impedance (Simulation results)

Figure 15. Motor start-up performance at duty ratio= 20 of R-C control of rotor impedance (Experimental results)
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