DEVELOPMENT OF AN INVERTER FED TWO-PHASE VARIABLE SPEED INDUCTION MOTOR DRIVE

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Abstract. This paper presents the modelling and experimental studies underlying the development of an inverter that is used as a supply for a variable speed two-phase induction motor drive. The inverter has four branches for the main and auxiliary windings of the motor. A special distribution is used for the windings. The drive system has a wide speed range in both directions. Several open-loop control strategies are examined using computer simulations on a 60 W two-phase induction motor.

Keywords: two-phase induction motors; inverter; control speed.

INTRODUCTION

The two-phase induction motor (TPIM) is used in many low power applications where three-phase supply is not readily available. The TPIM is usually a single-speed device operated from a fixed-frequency supply. Speed adjustments for two-phase and single-phase induction motors are normally realised by using tapped windings or voltage amplitude control, so the rotational speed is reduced by increasing the slip. But as efficiency is a function of slip, speed reductions lead to increased losses in the induction machine. Also, a limited speed range is obtained because steady-state operation is restricted to the stable zone of the torque-speed characteristic.

This paper proposes for speed-control of a TPIM, a pulse width modulation (PWM) inverter with four outputs connected to the special distributed windings of the motor. A wide speed range in both directions is achieved. As supply, a lead-acid battery or a bridge rectifier connected to the AC supply voltage is used. A comparison between a two-phase drive with induction motor supplied from a sinusoidal variable voltage amplitude and the same electric drive supplied from the PWM inverter is drawn. The first one was measured and the latter was computer simulated. Further experiments will be made to verify the accuracy of the simulation software.

THEORY OF THE TWO-PHASE INDUCTION MOTOR

The *d-q* model of an unsymmetrical two-phase induction machine in a stationary reference frame can be used for a dynamic analysis. The details of derivation of the *d-q* model as applied to TPIM are described in [1]. The equivalent circuit is shown in Fig. 1, and the machine model may be expressed by the following voltage and flux linkage equations [1]:

$$v_{QS} = R_m i_{QS} + (p/\omega_b)\lambda_{QS} \quad (1)$$

$$v_{DS} = R_a i_{DS} + (p/\omega_b)\lambda_{DS} \quad (2)$$

$$0 = R_r i_{QR} + (p/\omega_b)\lambda_{QR} - (1/k)(\omega_r/\omega_b)\lambda_{QR} \quad (3)$$

$$0 = R_r k^2 + (p/\omega_b)\lambda_{DR} + k(\omega_r/\omega_b)\lambda_{DR} \quad (4)$$

$$(p/\omega_b)\lambda_{feQS} = -R_{fe}\, i_{feq} \quad (5)$$

$$(p/\omega_b)\lambda_{feDS} = -k^2 R_{fe}\, i_{fed} \quad (6)$$

$$\lambda_{QS} = X_{sm} i_{QS} + X_m (i_{QS} + i_{QR} + i_{feq}) \quad (7)$$

$$\lambda_{DS} = X_{sa} i_{DS} + k^2 X_m (i_{DS} + i_{DR} + i_{fed}) \quad (8)$$

$$\lambda_{QR} = X_{sr} i_{QR} + X_m (i_{QS} + i_{QR} + i_{feq}) \quad (9)$$

$$\lambda_{DR} = k^2 X_{sr} i_{DR} + k^2 X_m (i_{DS} + i_{DR} + i_{fed}) \quad (10)$$

$$T_e = (P/2)(X_m / \omega_b)k[(i_{QS} + i_{feq})i_{DR} - (i_{DS} + i_{fed})\, i_{QR}] \quad (11)$$

The symbols used in equations (1)-(11) have the following definitions:

QS-axis parameters

R_m - stator main winding resistance

X_{sm} - stator main winding leakage reactance

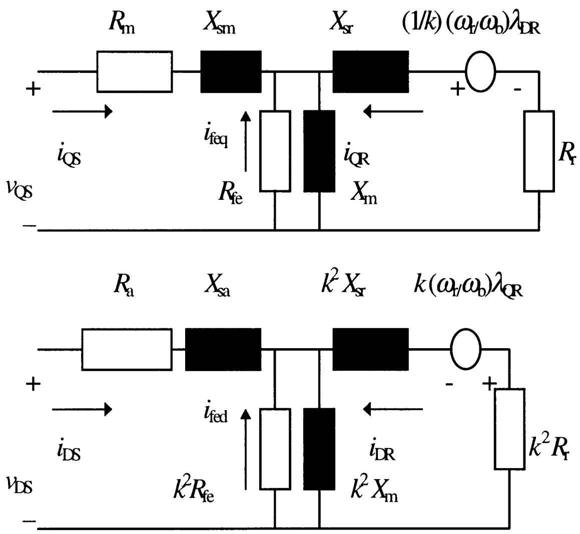

Fig.1 Equivalent circuit for a two-phase induction motor in transient state

X_m - QS-axis magnetizing reactance

X_r - rotor leakage reactance referred to stator main winding

R_r - rotor winding resistance referred to stator main winding

R_{fe} - equivalent iron loss resistance

DS-axis parameters

R_a - stator auxiliary winding resistance

X_{sa} - stator auxiliary winding leakage reactance

k - turn ratio between auxiliary and main stator windings.

Additional variables

v_{QS}, v_{DS} - QS-axis and DS-axis stator voltages

i_{QS}, i_{DS} - QS-axis and DS-axis stator currents

i_{feq}, i_{fed} - QS-axis and DS-axis iron losses equivalent currents

i_{QR}, i_{DR} - rotor currents referred to the stator QS- and DS-axes

p - differential operator d/dt

ω_b - base angular velocity

ω_r - rotor angular velocity.

Relation (11) expresses the instantaneous electromagnetic torque.

Assuming that the voltages and currents of the motor are sinusoidal, letting $p = j\omega$, and then substituting into (1) - (6), the steady-state equivalent circuit can be obtained as shown in Fig. 2 [1], where V_{QS+} and V_{QS-}

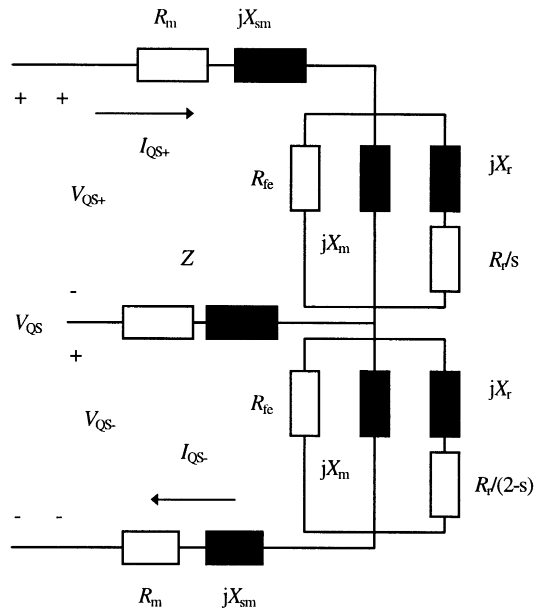

Fig.2 Equivalent circuit for a two-phase induction motor in steady-state operation

are the positive and negative sequence voltages, respectively. I_{QS+}, and I_{QS-} are the correspondent currents and s denotes the slip of the motor. The performance of the TPIM can be evaluated by using the equations:

$$Z = ((R_a / k^2 - R_m) + j\,(X_{sa} / k^2 - X_{sm}))/2 \quad (15)$$

$$V_{QS} = V_{QS+} + V_{QS-} \quad (16)$$

$$V'_{DS} = j\,(V_{QS+} - V_{QS-}) \quad (17)$$

$$V_{DS} = k\, V'_{DS} \quad (18)$$

$$I_{QS} = I_{QS+} + I_{QS-} \quad (19)$$

$$I_{DS} = (j/k)(I_{QS+} - I_{QS-}) \quad (20)$$

$$I_{QR+} = -I_{QS+}((jX_m \| R_{fe}) + R_r/s + jX_r)/(jX_r + R_r/s) \quad (21)$$

$$I_{QR-} = -I_{QS-}((jX_m \| R_{fe}) + R_r/(2-s) + jX_r)/(jX_r + R_r/(2-s)). \quad (22)$$

$$T_{e(avg)} = P(X_m/\omega_b)(\mathrm{Re}(j(I^*_{QS+} I_{QR+} - I^*_{QS-} I_{QR-})) \quad (23)$$

$$T_{e(puls)} = P(X_m/\omega_b)(\mathrm{Re}(j(-I_{QS+} I_{QR-} + I_{QS-} I_{QR+}))\cos 2\omega t + \mathrm{Re}(I_{QS+} I_{QR-} - I_{QS-} I_{QR+})\sin 2\omega t) \quad (24)$$

Clearly, the level of magnetisation for the two-phase induction motor is dependent on both the positive and negative induced voltages, which are in turn dependent on the operating conditions of the motor. The magnetizing currents in the positive and negative branches are found by current division from Fig. 2:

$$I_{QSm+} = I_{QS+}((jX_m \| R_{fe}) + R_r/s + jX_r)/(jX_m) \quad (25)$$

$I_{QSm-} = I_{QS-}\,((jX_m|\,|R_{fe})+R_r/(2-s)+jX_r)\,/(jX_m)$ (26)

By solving (16) through (26) simultaneously, the TPIM's performance can be predicted. Each reactance is assumed to behave linearly with frequency (the inductances are assumed constant) for a given slip.

SYSTEM DESCRIPTION

The voltage supply is 10...15 V DC for a two-phase PWM inverter. It is possible to supply the main and auxiliary windings of the motor with two 12 V_{rms} voltages with a variable mutual phase shift. The PWM inverter is implemented with power transistors (MOSFET) and logic circuits. Each of the two windings comprises two parallel identical windings. So four windings, in total, are connected to four outputs from the inverter as shown in Fig. 3. Here V_{rm} denotes the resultant voltage for the main winding of the motor and V_{m+} and V_{m-} are the components of V_{rm}, provided for windings m1 and m2. The auxiliary winding is connected in a similar way. By logic control, the windings are supplied with separate voltages and the motor can rotate in both directions. The phase angle between the currents (main and auxiliary) is variable, so the resultant revolving field is quasi-circular or elliptic. For example, the clockwise rotation is obtained with windings m1 and a1 supplied with positive pulse and m2 together with a2 supplied with negative pulse. The counterclockwise rotation is obtained with m1 and a2 on positive pulse and m2, a1 on negative pulse.

The original motor is a capacitor run two-phase induction motor driving an air compressor. The control circuit for the single-phase induction motor with balanced windings consists of controller with two closed loops: one loop for main current and another one for auxiliary current.

The power circuit is built using one power module comprising twelve bipolar transistors. These switches operate as centre tap inverter circuits producing the PWM variable voltage-variable frequency (*V-f*) output across the two windings of the motor. Full 12 V_{rms} operation of the two windings is possible.

The dynamic modelling of the inverter fed TPIM has been carried out considering a sinusoidal spatial distribution for the main and auxiliary windings.

The main and the auxiliary windings are nonidentical, so that the controller ratio *V-f* for the two windings was selected according to

$$V_{aux} = k\, V_{main} \qquad (27)$$

This maintains the ampere-turns of the two windings roughly the same at all frequencies. Voltages V_{rm} and V_{ra} for the two windings can be in quadrature at all times.

The inverter fed system can be adapted to every type of single- and two-phase induction motor (split-phase, capacitor start, capacitor run motors or servomotors).

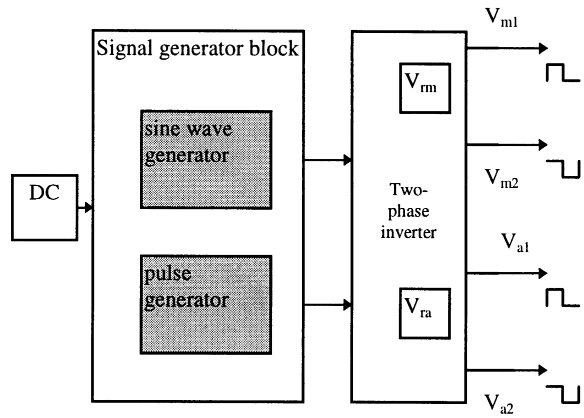

Fig. 3. Block diagram of the two-phase inverter

RESULTS SIMULATED FOR STEADY AND DYNAMIC STATES

A sample 60 W capacitor run TPIM was used for the simulations using symmetrical components for steady-state operation and *d-q* model for transient state analysis. The model parameters were obtained from laboratory tests. The simulated torque-speed characteristics in an open-loop-control using a constant voltage-frequency ratio and relation (14) between the main and auxiliary voltages are depicted in Fig. 4. The switching frequency for the PWM is 1 kHz and the maximum input voltage is 17 V_{rms}.

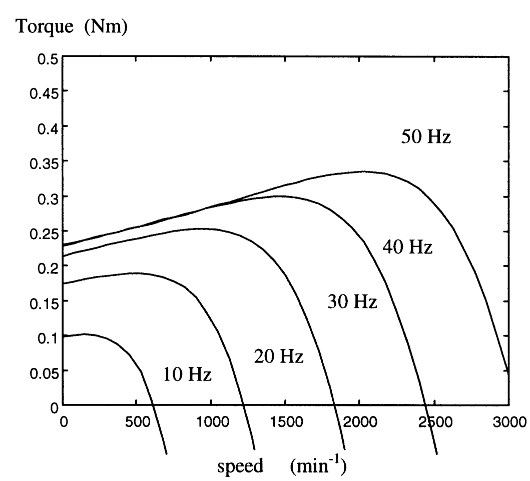

Fig. 4. Torque-speed characteristics of a TPIM for several frequencies using a constant V/Hz ratio

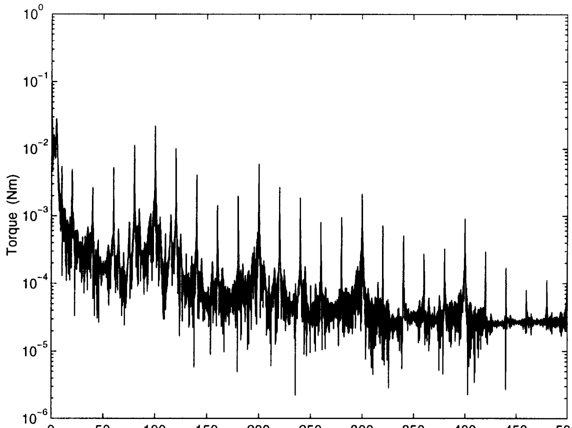

Fig. 5. Torque harmonic content , simulated for PWM supply. The rated frequency is 50 Hz.

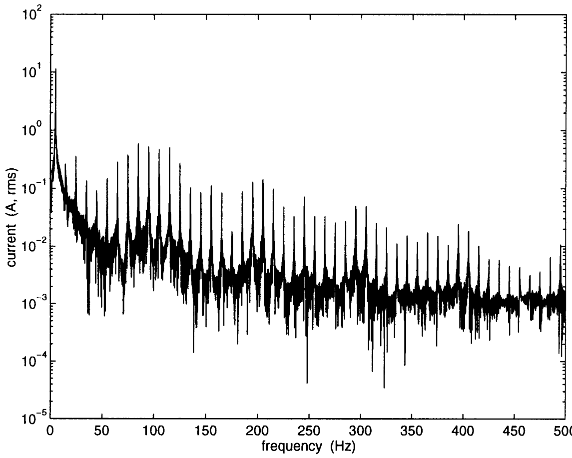

Fig. 6. Line current harmonic content, simulated for PWM supply. The rated frequency is 50 Hz.

Note that at the lower frequencies a larger relative decrease in the speed (slip increases) is needed to obtain the rated torque. The starting torque reaches a maximum when the frequency is between 40 and 50 Hz.

Figs. 5 and 6 show the harmonic content of the instantaneous torque and line current in transient state operation, from standstill to the rated speed. A wide range of harmonics is present, but with small amplitudes. The double supply frequency pulsating torque is almost indistingtible from the other harmonic components. The total rms harmonic current is computed from

$$I_{\mathrm{h}} = \sqrt{I_{\mathrm{s}}^2 - I_{50}^2} \qquad (28)$$

where I_s is the rms line current and I_{50} is its 50 Hz component. The total harmonic distorsion (THD) of the line current may be calculated as I_h / I_{50}. At the rated speed 2900 min^{-1} , the calculated THD obtained by computer simulation is 62.3%. Harmonic distorsion can be reduced by increasing the switching frequency of the PWM. The simulation model predicts a low level for the pulsating torque, but further investigation is necessary in order to consider the mechanical variables which have been neglegted in this model.

EXPERIMENTAL RESULTS

For comparison with the computer simulated model, a capacitor run single-phase induction motor is tested. As a supply a variable sinusoidal voltage is used. The maximum voltage amplitude is 12 V AC. The motor parameters are identical with those implemented in the TPIM computer model.

Fig. 7 illustrates the torque-speed characteristics for the capacitor run motor when using the classical method of voltage amplitude control at constant frequency. The capacitance value used for balanced operation is 850 μF.

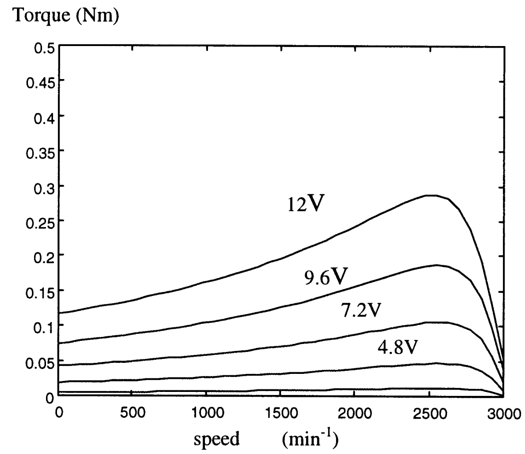

Fig. 7. Torque-speed characteristics of a TPIM for variable voltage and constant frequency

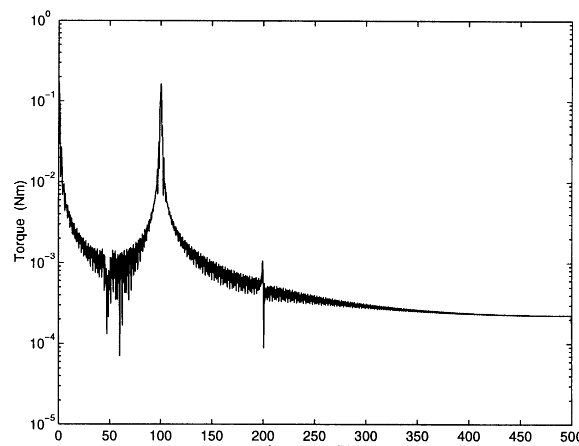

Fig. 8. Torque harmonic content , measured for sinusoidal voltage supply.
The rated frequency is 50 Hz.

The break-down torque is lower than that one simulated for the PWM inverter fed TPIM. The rated torque

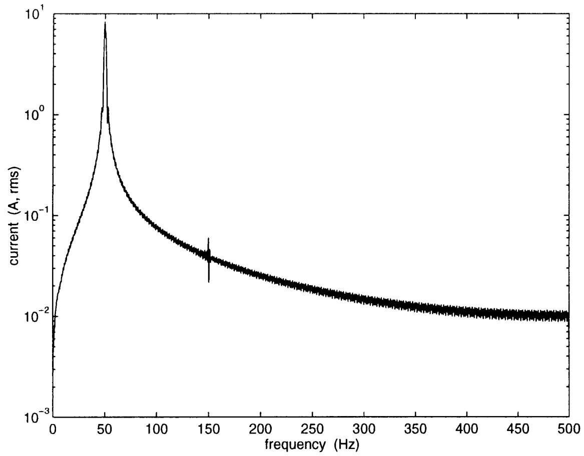

Fig. 9. Line current harmonic content, measured for sinusoidal supply. The rated frequency is 50 Hz.

decreases rapidly when the voltage amplitude is reduced from the rated value to a lower value.

Fig. 8. demonstrates that the main vibrational torque in normal single-phase induction motor is produced by the double frequency supply pulsating torque. The other harmonic components are negligible.

By comparison with Fig. 5, it is important to observe that the instantaneous torque of a two-phase induction motor connected to an inverter has a smaller pulsating component than the capacitor run motor.

In Fig. 9. the line current harmonic content is depicted. Total harmonic distorsion of the line current when a sinusoidal voltage is used is much lower than that one calculated in the PWM inverter fed TPIM's case. At the rated speed (2900 min^{-1}) the measured THD is 1.2%.

CONCLUSIONS

The inverter fed two-phase induction motor is a workable replacement for the capacitor run single-phase induction motor. The model of the new drive system has been simulated on computer. A comparison was made between the inverter fed two-phase variable speed induction motor and the capacitor run drive system of a single-phase induction motor.

The simulation and the experiments showed the following:

- The inverter fed system gives direct control of the motor speed by using the combined strategy: constant voltage -frequency ratio and auxilary-main amplitude voltage ratio equals with turns windings ratio.
- The instantaneous torque of a two-phase induction motor connected to an inverter has a smaller pulsating component than the capacitor run motor.
- The inverter fed system can be adapted to every type of single- and two-phase induction motor (split-phase, capacitor start, capacitor run motors or servomotors).

APPENDIX - MOTOR DATA

Two -phase induction motor :
(30 W, 12 V, 50 Hz, 8.5 A, 2 pole)
$R_m = 0.34\ \Omega$; $X_{sm} = 0.08\ \Omega$;
$R_a = 0.76\ \Omega$; $X_{sa} = 0.16\ \Omega$;
$R_{fe} = 19.48\ \Omega$; $X_{m\cdot} = 3.24\ \Omega$;
$R_r = 0.34\ \Omega$; $X_r = 0.11\ \Omega$;
Auxiliary - Main Turns ratio (k) = 1.38.

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