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Control of Zero Sequence Braking for a Three-phase Induction Motor Operating from Single-phase Supply with a Controlled Capacitor

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Abstract: Studying of braking process in the Alternating Current (AC) motors has a great importance due to the need for reducing the braking and stopping time. In many applications, it may be necessary to use a three-phase induction motor on a single-phase supply system. The aims of this study are to investigate and discuss the behavior of a three-phase induction motor operating from single-phase supply when steady-state zero-sequence braking is used. Therefore, mathematical model was developed and the symmetrical components' method was used. To verify the obtained results, an experiment was performed and oscillograms of transient speed were recorded. Results show that the synchronous speed under braking has fallen to one-third of the motoring synchronous speed. And it was also observed that braking time can be controlled by changing the capacitance and rotor resistance values.

Key words: Transient response, zero sequence braking, regenerative braking, mathematical modeling, capacitor-run induction motor, control of electrical machines

INTRODUCTION

Single-phase induction motors are as ubiquitous as they are useful, serving as the prime power sources for a seemingly limitless array of small-horsepower applications in industry and in the home, especially in Heating, Ventilation and Air Conditioning (HVAC) systems (Chomat, 2003; Li and Cathey, 2006).

In many applications, it may be necessary to use a three-phase induction motor on a single-phase supply system. For example, it has been found technically and economically advantageous to initially install a Single Wire Earth Return (SWER) system for rural electrification in remote and hilly regions (Ahmed, 2005).

Utilizing of Friction braking may lead to break wearing, bearing amortization, thermal cracks and thermally-excited vibration due to the temperature rise resulting from the braking process (Talati and Jalalifar, 2008). Therefore, electric braking is necessary to solve these problems.

In zero sequence braking, three stator phases are connected in series across a single phase AC source. Such a connection is known as a zero sequence connection. The switching arrangement, from normal three-phase to zero sequence operation, is extremely simple when the motor has a delta-connected stator and can be structured as in Fig. 1 (Ahmed, 2005; Dubey, 2002).

The developed torque of a three phase induction motor is significantly reduced when a condenser is inserted in series in one of the supply lines (Sreenivasan, 1959). Also, zero-sequence parameters and parameter variations can be determined (Grantham, 1983).

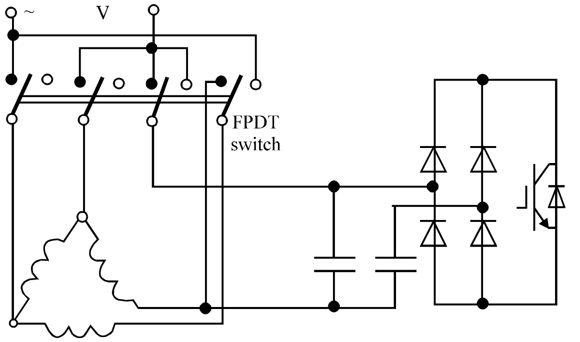

Fig. 1: Zero sequence braking of a three-phase induction motor operating from single-phase supply with a controlled capacitor

The magneto-motive force caused by cophasal currents (or zero sequence) produces a magnetic field having three times the number of poles for which the machine is actually wound (Dubey, 2002) because of evolving third spatial harmonics as a result of summing the phase-magnetizing forces (Chycbar, 1967). Thus the motor works momentarily in regenerative braking mode and generated energy is supplied to the source or energy storage device (Bai *et al*., 2005). Braking could be used almost up to one-third of synchronous speed if the load torque is less than the maximum torque (Dubey, 2002), otherwise motor speed will fall to zero.

For the fixed value of motor terminal voltage, the braking torque is not regulated and the motor has a strict speed-torque characteristic nature. The speed is conventionally controlled using either winding tappings, variac, autotransformer, or series impedance (Abdel-Halim, 1999). In order to control the braking torque and, consequently, the nature of the mechanical characteristics, it is necessary to vary the motor terminal voltage. Use of controlled-voltage supply leads to difficulty and complexity of the electric drive system. So, in this case and for the ease of control and balance (Obea *et al.*, 2007), it is more convenient to use series impedance (capacitors), where the phase-shift capacitor may play the role of voltage-divider. Thus, changing the motor terminal voltage is available by regulating the value of condenser-capacitance. Since the value of capacitance can be controlled electronically, braking control will become smooth and one capacitor can be used (Ahmed, 2005). Motor behavior was investigated at three values of capacitance.

The aims of this study are to investigate and discuss the behavior of a three-phase induction motor operating from single-phase supply when steady-state zero-sequence braking is used. For this purpose, simulation is carried out and braking time is monitored for variable values of capacitance and rotor resistance.

MODELING OF MOTOR OPERATION

Expressions used to simulate the motor operation can be obtained from the equivalent circuit when the machine works on regenerative braking (Pillai, 2004), Fig. 2 shows the equivalent circuit for both positive and negative sequence components.

From this circuit, voltage and current equations are:

$$\dot{V} = \dot{V}_m + \dot{V}_K \tag{1}$$

$$\dot{I}_m = \dot{I}_K = \dot{I}_1 = \dot{I}_2 \tag{2}$$

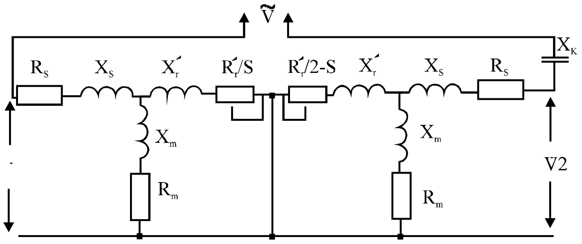

Fig. 2: Per-phase equivalent circuit

Resolving currents and voltages into symmetrical components (Alshamasin, 2005, 2009; Popescu *et al.*, 2005) gives:

$$\dot{V}_m = \dot{V}_1 + \dot{V}_2 \tag{3}$$

$$\dot{I}_{1(2)} = \frac{\dot{V}_{1(2)}}{Z_{1(2)}} \tag{4}$$

Substituting the voltage and current values from Eq. 3 and 4 into Eq. 1, yields:

$$\dot{V}_1(1 + \frac{Z_K}{Z_1}) + \dot{V}_2 = \dot{V} \tag{5}$$

$$\dot{V}_1 + \dot{V}_2(1 + \frac{Z_K}{Z_2}) = \dot{V} \tag{6}$$

Solving Eq. 5 and 6 gives:

$$\dot{V}_1 = \dot{V}\frac{Z_1}{Z_1 + Z_2 + Z_K} \tag{7}$$

$$\dot{V}_2 = \dot{V}\frac{Z_2}{Z_1 + Z_2 + Z_K} \tag{8}$$

By the obtained symmetrical components of voltages, maximum torque values can be determined as:

$$T_{1max} = \left|\frac{V_1}{V}\right| T_{max} \tag{9}$$

$$T_{2max} = \left|\frac{V_2}{V}\right| T_{max} \tag{10}$$

Then the developed motor torque will be:

$$T = T_1 - T_2 = \frac{2T_{1max}(1+a)}{\frac{S_{cr}}{S} + \frac{S}{S_{cr}} + 2a} - \frac{2T_{2max}(1+a)}{\frac{S_{cr}}{2-S} + \frac{2-S}{S_{cr}} + 2a} \tag{11}$$

Where:

$$a = \frac{R_1}{R_2'} S_{cr}$$

For the same motor, the critical slip value when it is fed from single-phase supply voltage (S_{er}) differs from that (S_{er3}) of three-phase operation mode (fed from three phase supply voltage) and $S_{cr} = 2.25S_{cr3}$ (Feelts, 1970). Hence, the number of poles increases, so the rotor resistance under each stator pole decreases. Also, the capacitor affects the critical slip, so:

$$S_{cr} = kS_{cr3} = \frac{kR_r'}{\sqrt{R_S^2 + (X_S + X_r' - X_K)^2}} \tag{12}$$

where, coefficient (k) can be found for a particular motor by experiment.

SIMULATION AND RESULTS

Conventional braking technique (Regenerative, plugging, dynamic) for three phase motor operating from three phase supply were discussed and advantages and disadvantages were stated by Rongmei *et al.* (2012). This study investigates the behavior of the three phase motor fed from single phase supply when it is braked by zero sequence method.

In order to investigate the motor characteristics, simulation by using lab VIEW software was carried out. The motor used for simulation and experimental in this study was 3.75 hp, four poles, 220 volt, three phase induction motor. The motor data are as follows:

Stator resistance:	1.95 Ohm
Rotor resistance:	3.12 Ohm
Stator reactance:	3.43 Ohm
Rotor reactance:	3.43 Ohm
Magnetizing reactance:	3.40 Ohm
Magnetizing reactance:	71.4 Ohm
Rated speed:	1370 rpm

Figure 3 shows the mechanical characteristics of motor regenerative braking for three values of capacitance (C = 100, 200, 300 μF).

It is obviously seen from Fig. 3 that capacitance (C) plays the role of the horizontal parameter affecting the amplitude of torque.

To illustrate the influence of capacitance and resistance on the motor braking, the behavior of the motor was investigated experimentally. The motor shaft is coupled to a DC generator (load) whose inertia is five times the motor's value Fig. 4.

Figure 5 shows the oscillogram of the speed dynamic characteristics (transient characteristics) for the slip-ring motor with different values of capacitance (C) and resistance (R_{2add}). The sampling time has been set

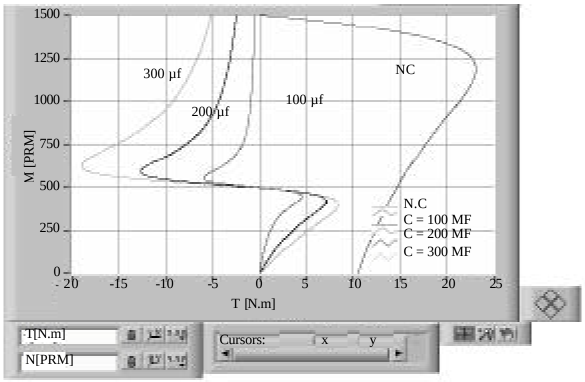

Fig. 3: Speed-torque characteristics

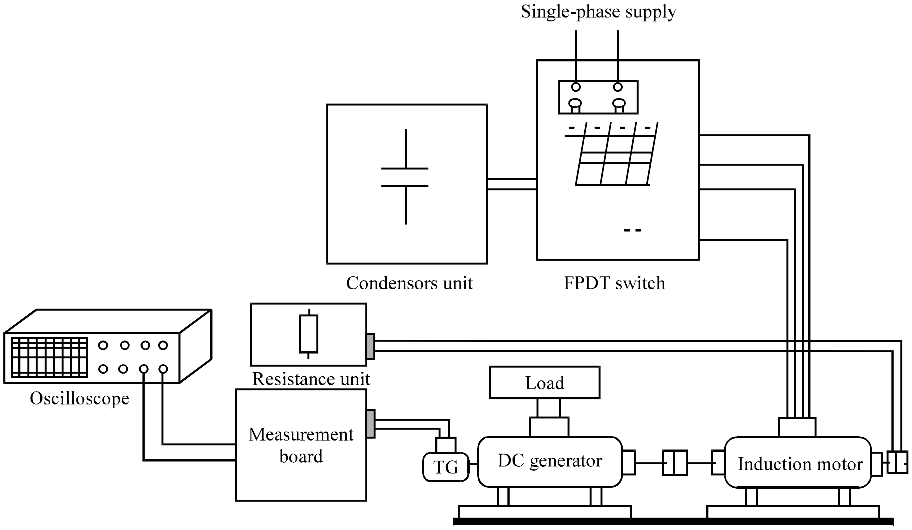

Fig. 4: Experimental setup of system

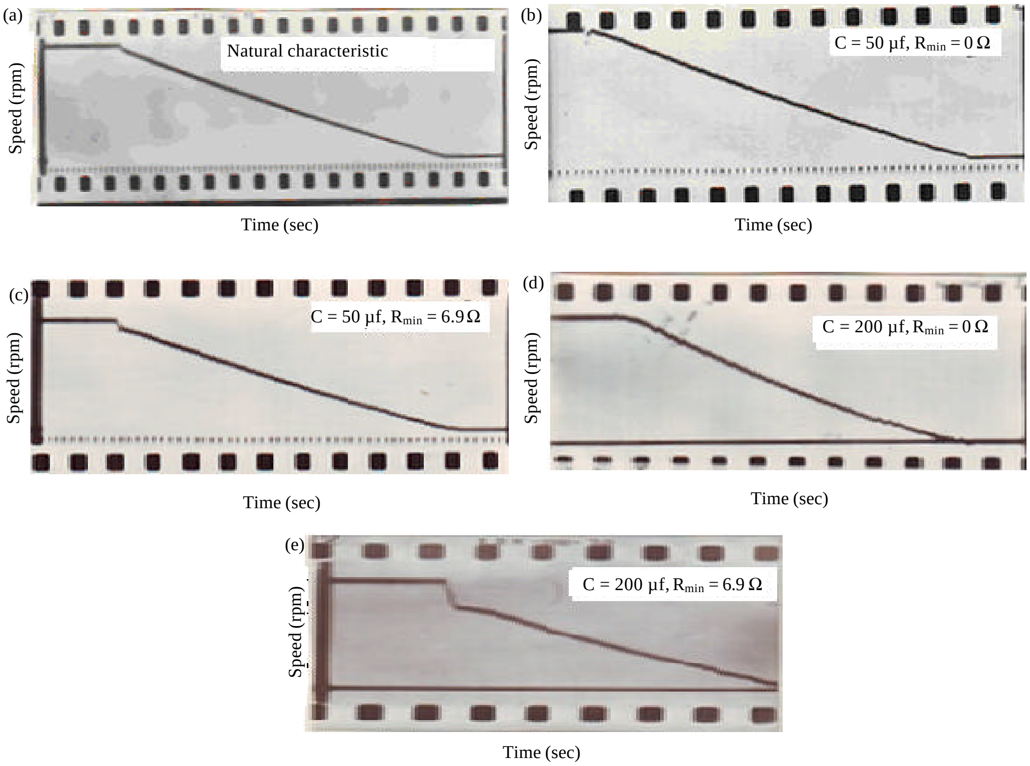

Fig. 5(a-e): Instantaneous speed vs. time when the motor operates in the braking mode for, (a) Natural characteristic, (b) C = 50 μF, R_{add} = 0 Ω, (c) C = 50 μF, R_{add} = 6.9 Ω, (d) C = 200 μF, R_{add} = 0 Ω and (e) C = 50 μF, R_{add} = 6.9 Ω

to 0.1 sec. It is noticeable that increasing the added resistance or capacitance results in decreasing the braking time. Fig. 5e shows that inserting resistance into the rotor circuit with high value of capacitance in the stator circuit will lead to self-excited braking and short stopping time. Uniform decelerations are obtained for almost all portions of the curves.

Superior to other braking methods, utilizing of capacitor and rotor resistance in zero sequence braking gives the ability to control the braking time and satisfy fast stopping due to the uniform of the braking current. Unlike the dc injection braking system, the braking current due to the zero sequence will flow in all the three windings of the stator and also distribution of magnetic field due to the braking current will be more uniform (Kostelnicek, 2001). Also, zero sequence braking does not need additional voltage source which requires additional devices (Nasir, 2012). More devices will lead to complexity of the braking circuit and existence of harmful harmonics (Letenmaier *et al.*, 1991; Alshamasin, 2005).

Regenerative brake is an energy recovery mechanism (Cholula *et al.*, 2005) but braking drops off at lower speed and cannot bring the motor to a complete halt (Pengyu *et al.*, 2009). Frequent plugging (counter current braking) can create serious overheating (Rongmei *et al.*, 2012), moreover, there is a possibility of reversing the motor rotation if the zero speed detector fails to remove the braking as soon as the motor speed reached to zero rpm (Dubey, 2002).

CONCLUSIONS

A mathematical model is developed for steady-state zero-sequence braking performance of a three-phase induction motor operating from single-phase supply with a controlled capacitor. The obtained mechanical characteristics show that t his kind of braking can be used for both squirrel-cage and wound-rotor motors alike, since it does not require large rotor resistance. Intensive and self-excited braking could be caused if resistance is inserted into the rotor circuit with high value of capacitance in the stator circuit, which ensures rapid stopping of induction motors. Results show that the braking time can be controlled by changing the capacitance and rotor resistance values.

This method, compared with the dynamic braking connection which requires a DC source or AC source with high rotor circuit resistance, is worthy of serious consideration.

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