

Proposed Scheme for Plugging Three-Phase Induction Motor

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ABSTRACT - The paper presents a proposed scheme for fast braking of induction motor drive system. The proposed braking strategy is based on the injection of an AC voltage to the rotor winding from three-phase SVPWM inverter during braking. The injected voltage must have the same frequency, same phase shift and opposite in direction to the rotor induced voltage. The purpose of this method is to reduce the rotor and stator high currents during reverse current braking (plugging), to an acceptable value. A model of the proposed braking strategy is implemented using the well known Matlab/Simulink software package. The different characteristics of the drive system are investigated and the usefulness of the braking system is verified with a special consideration given to the currents in the machine during braking.

I. INTRODUCTION

The induction motor is a rugged, reliable, low maintenance and less expensive machine. Therefore, with the advent of power electronic switches, the most cost effective method to design variable voltage/frequency power supply using the semiconductor switches for induction motors have been utilizing[1].

Braking is one of important questions in electrodynamics machine system. During production, in order to decrease auxiliary work time, to raise production efficiency, to realize halt exactly, to improve product quality, to ensure personal safety and so on, a great deal of machines require effective braking. In electrodynamics machine system, the application of asynchronous machine is extensive; so it is of great significance to research braking of asynchronous machine deeply. The electrical braking methods for three-phase asynchronous machine have: regenerative braking, plug braking, dynamic braking and so on[2]. The deceleration stopping method requires careful selection of the deceleration time to achieve optimum stopping performance[3].

It is sometimes necessary to stop quickly or decelerate the induction motor under controlled condition as when lowering a load in a crane or hoist. Such retardation is effected to by providing a braking torque. Plugging is one of the electrical braking methods applicable in the case of induction motor[4]. The principle of traditional plug braking is that

changing the direction of revolving magnetic field to oppose the direction of former magnetic field by changing the phase sequence of three-phase voltage, then the motor will be braked by opposing torque in a short time [5]. If the leads on the stator windings are reversed suddenly, the direction of rotation for the stator field is reversed. The resulting slip is larger than one. The motor will come to an abrupt stop. The motor must then disconnected from the voltage source before it starts to rotate in the reverse direction, this method of bringing motors to a quick stop is commonly known as plugging. Reverse-current braking (plugging) is very effective but consumes approximately three times the stored kinetic energy of the system in reducing the speed to zero, and would run up as a motor in reverse rotation unless prevented[6].

A simple braking technique has been developed for improvement plugging performance of the wound rotor induction motor using a SVPWM inverter in the rotor side for injection of 3-phase ac voltage in the rotor circuit

The results presented in this work validate the effectiveness of proposed technique of gaining fast braking with no high braking current at different operating conditions.

II. PLUGGING BRAKING CONCEPT

Plugging indicates that counter torque braking is obtained by reversing or reconnecting the power input leads of certain types of motors which may be running at any speed. Plugging provides simple and fast braking action but with high braking current which is severe unless limited by resistors in series with the motor windings. Motor windings may require additional bracing. The motor will reverse direction of rotation unless removed from the line at zero speed by an operator, a zero-speed switch, or a timer. Losses are high during plugging, reaching three times the acceleration loss for a squirrel-cage motor (four times if the motor is allowed to accelerate to full speed in the reverse direction). Value of braking torque can be varied by any means which varies the current flowing in the windings[7].

Plug braking is obtained by changing the phase sequence of the input voltage where the whole energy is dissipated in the motor[8]. External resistance is inserted when operating in the plugging mode, this reduces the current, improves the power factor and

increase the braking torque. Rotor resistance control is of course confined to phase-wound rotors with slip rings[9]. The supply voltages before and after plugging are given in TABLE I[10].

TABLE I
MOTOR SUPPLY VOLTAGES.

Before Plugging	During Plugging
$v_a = V_m \sin(\omega t)$	$v_a = V_m \sin(\omega t)$
$v_b = V_m \sin(\omega t - 2\pi/3)$	$v_b = V_m \sin(\omega t + 2\pi/3)$
$v_c = V_m \sin(\omega t + 2\pi/3)$	$v_c = V_m \sin(\omega t - 2\pi/3)$

III. PROPOSED SCHEME FOR INDUCTION MOTOR PLUGGING

Induction motor model has been in use and is well characterized both experimentally and theoretically. It has also been derived in a number of different reference frames. For control purposes the model is often expressed in a two-axis rotating reference frame. This makes it easier for the control designer to fix the reference frame to a particular motor quantity and adjust the model accordingly.

Induction motor model in the synchronous rotating reference frame is given as[11]:

$$\begin{aligned}
v_{sd} &= R_s i_{sd} + p \lambda_{sd} - \omega_s \lambda_{sq} \\
v_{sq} &= R_s i_{sq} + p \lambda_{sq} + \omega_s \lambda_{sd} \\
v_{rd} &= R_r i_{rd} + p \lambda_{rd} - (\omega_s - \omega_r) \lambda_{rq} \\
v_{rq} &= R_r i_{rq} + p \lambda_{rq} + (\omega_s - \omega_r) \lambda_{rd} \\
T_e &= \frac{3}{4} PL_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \quad \dots\dots\dots(1) \\
\lambda_{sd} &= L_s i_{sd} + L_m i_{rd} \\
\lambda_{sq} &= L_s i_{sq} + L_m i_{rq} \\
\lambda_{rd} &= L_m i_{sd} + L_r i_{rd} \\
\lambda_{rq} &= L_m i_{sq} + L_r i_{rq}
\end{aligned}$$

The motor mechanical dynamics is represented according to the following equation:

$$T_e = J \frac{d\omega_r}{dt} + F \omega_r + T_L \quad \dots\dots\dots(2)$$

where

Indexes “r” and “s” represent rotor and stator respectively.
Indexes “d” and “q” represent direct axis and quadrature axis respectively.
 v is the voltage.
 i is the current.
 λ is the flux linkage.
 R is the resistance.

ω_s is the stator revolving field speed in rad/sec.

ω_r is the rotor speed in rad/sec.

$$p = \frac{d}{dt}$$

T_e is the developed electromagnetic torque in Nm.

T_L is the load torque in Nm.

P is the number of poles.

L_m is the magnetizing inductance.

L_s and L_r are the stator and rotor self inductances.

J is the rotor inertia constant in kg.m².

F is the viscous friction constant in Nm.sec.

The basic concept of the proposed braking strategy is based on the injection of an AC voltage to the rotor winding from three phase SVPWM inverter during plugging (reverse current braking). The injected voltage must have the same frequency, same phase shift and opposite in direction to the original rotor induced voltage. This can be satisfied by taking samples of rotor currents (i_{ra}, i_{rb}, i_{rc}). This will provide an idea about the three-phase voltage in the rotor circuit. These samples are used as reference voltages for the SVPWM inverter. Accordingly, motor model given in Eq.(1) can be rewritten to match with this braking strategy as follows:

$$\begin{aligned}
-v_{sd} &= R_s i_{sd} + p \lambda_{sd} + \omega_s \lambda_{sq} \\
v_{sq} &= R_s i_{sq} + p \lambda_{sq} - \omega_s \lambda_{sd} \\
v_{rd} - v_{jd} &= R_r i_{rd} + p \lambda_{rd} - (\omega_s - \omega_r) \lambda_{rq} \quad \dots\dots\dots(3) \\
v_{rq} - v_{jq} &= R_r i_{rq} + p \lambda_{rq} + (\omega_s - \omega_r) \lambda_{rd}
\end{aligned}$$

where v_j is the rotor injected voltage.

The purpose of this braking strategy is to reduce the rotor and stator high currents during the reverse current braking (plugging) to be within acceptable values and to quickly stop the induction motor. The proposed scheme can also be used to quickly reverse motor direction of rotation. This is done with at the same time lowering the high motor reversed current. The model of the proposed braking strategy is implemented using the well known Matlab/Simulink software package. This Matlab/Simulink implementation is shown in Fig.1. In this figure, k_j represents the gain factor of the rotor injected voltage. The block B1 is an electronic circuit which initiates the braking process and also disconnected the motor terminals from the three-phase supply system when the speed reaches near zero. While block B2 enables the three-phase inverter voltage to be injected to the motor rotor circuit only during the reverse current operation, i.e. during braking or speed reversal. The different characteristics of the drive system will be investigated and the usefulness of the braking system will be verified with a special consideration will be given to the currents in the machine during the braking.

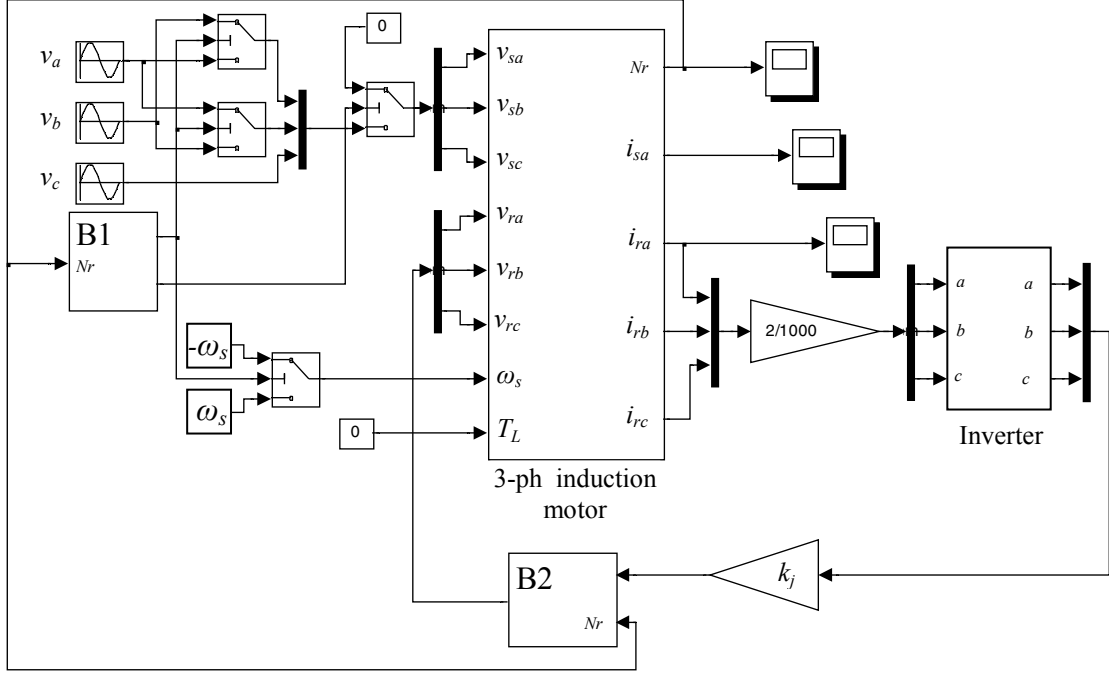


Fig.1. Matlab/Simulink implementation of the proposed braking strategy.

IV. SIMULATION RESULTS OF THE PROPOSED PLUGGING STRATEGY

To confirm validity of the proposed braking strategy, the Matlab/Simulink model is tested under different operating conditions. The test results are given in Figs.2-6. For the sake of testing, the value of the injected voltage gain factor (k_j) is chosen to vary between (0 and -5) in order to study the influence of the ac injected voltage on the motor currents and also on the time of braking.

The relationship between the amount of injected voltage (decided by factor k_j) and the braking time at different loads is shown in Fig.2. The load is changed between 0 Nm and 400 Nm in steps of 50 Nm. It can be shown from these curves that the minimum braking time occurs with ($k_j = -1.5$) for all loads. Therefore, this value is suggested to perform plugging of the selected three-phase induction motor. A comparison is made between normal shutdown, dynamic braking, and plugging using the proposed method. The result is shown in Fig.3. It is clear from this figure that plugging (with $k_j = -1.5$) is much faster braking than dynamic braking or normal shutdown. While, Figs.4 and 5 compare the stator currents with $k_j = 0$ and -1.5 respectively, i.e. without and with voltage injection. These two figures prove clearly the effectiveness of the proposed strategy of reducing the motor current during plugging. The braking current is less known than the starting current.

The curves shown in Fig.2 state that the magnitude of the injected voltage gain factor (k_j) can be increased even to -5 and still the proposed braking method be faster than without voltage injection. This increase in k_j will reduce the motor current significantly. This is shown in Fig.6. A comparison between

Figs.5 and 6 shows the great improvement in stator braking current. The braking current is only little more than full load current.

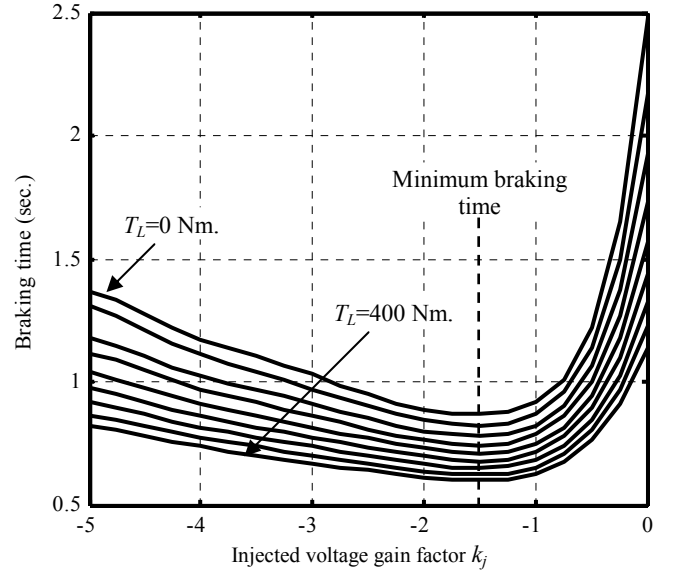


Fig.2. Relationship between braking time and the injected voltage gain factor (k_j) for different load torques.

V. CONCLUSION

A method for braking wound-rotor three-phase induction motor has been suggested to improve the braking performance, i.e. braking time and current. The main idea of this method

stands on the injection of three-phase voltage in the rotor circuit during the plugging braking process. This injected voltage is supplied by SVPWM inverter. The inverter operation depends on taken samples of the rotor voltage to ensure that the injected voltage has the same frequency, same phase shift, and in phase opposition to the rotor induced voltage. The whole system is simulated using Matlab/Simulink software.

The results presented throughout this work prove the validity of the proposed method in decreasing the braking time and current. The current is only little more than full load current with high values of injected voltage gain factor (k_f). Also, the braking time is less than another braking methods.

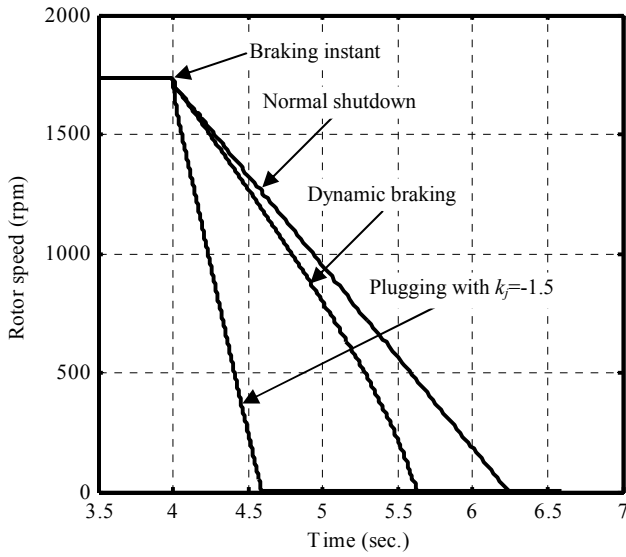


Fig.3. Rotor speed for normal shutdown, dynamic braking, and proposed braking method with a load of $T_L=400$ Nm.

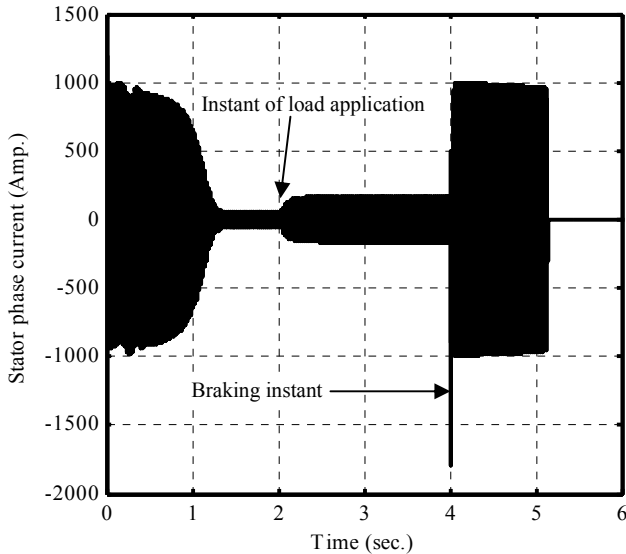


Fig.4. Stator phase current before and after plugging with $k_f=0$ and a load torque of $T_L=400$ Nm.

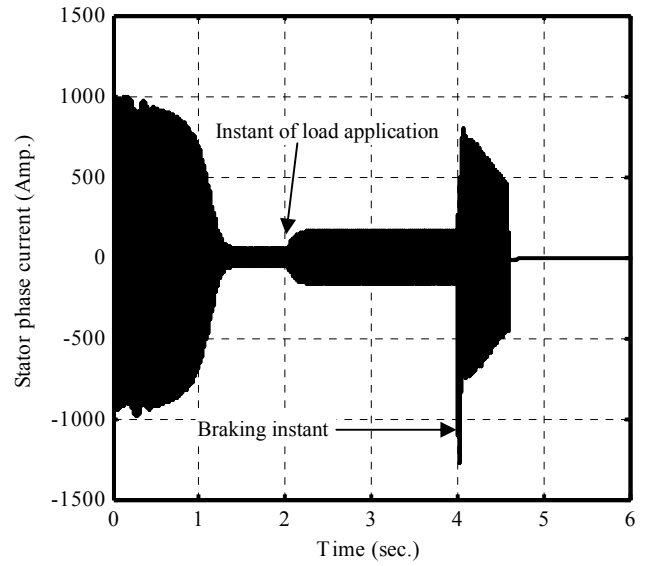


Fig.5. Stator phase current before and after plugging with $k_f=-1.5$ and a load torque of $T_L=400$ Nm.

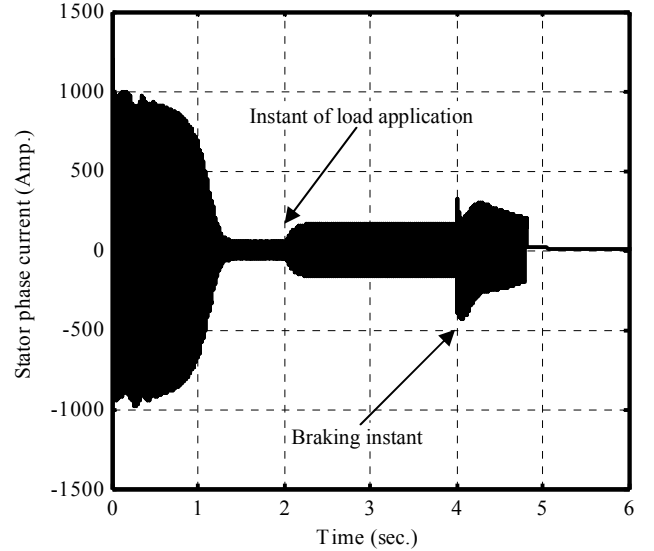


Fig.6. Stator phase current before and after plugging with $k_f=-5$ and a load torque of $T_L=400$ Nm.

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