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Experimental Investigation on the Speed Control and Power Factor Improvement of a Novel Induction Machine with Rotating Power Electronic Converter

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Abstract—A novel speed control strategy of an induction machine with RPEC (rotating power electronic converter) is investigated in this paper. The stator of the machine is directly connected to the power distribution network while the open-ended rotor windings are connected to a back-to-back converter. A dynamic model is developed in the three-phase reference frame. Dynamic performance of the starting process of the system is studied, based on an 1.8kW induction machine in the laboratory. Experimental results have shown that constant speed control is achieved in a simple manner by controlling the rotor current frequency. Importantly the stator power factor can be improved effectively within a wide range of load variation including the rated load. Moreover, the dc-link voltage over the capacitor between the two converters is considerably low which implies a great reduction of the capacitor size.

Index Terms—Speed control, rotating power electronic converter, power factor, induction machine

I. INTRODUCTION

This paper investigates the transient performance of a novel topology of an induction machine with rotating power electronic converter [1]-[3]. There are mainly three different methods to control the speed of a wound rotor induction machine [1]. One solution which was common in the past is to connect resistors to the rotor windings [1], [4]. Nowadays this method is mainly used to start large motors in order to obtain a high starting torque and a low starting current drawn from the grid. Due to the low efficiency, this method is very seldom used for speed control in practice [1], [5]. In [4], rotor impedance control with different combinations of resistors, inductors and capacitors as well as their connections is investigated. It is shown that different schemes are suitable for specific speed settings in order to get good speed regulation performance and high power factor. However, this method is preferred for applications where precise speed control is not required and where speeds are close to the synchronous speed [6].

An alternative method for speed control is presented in [7], where the slip ring voltage is rectified instead of being connected to the resistors. The rectified voltage is then inverted to three phase voltages and fed back to the grid, which thus reduces the losses drastically. The use of through-pass inverters for speed control in the slip power recovery system is particularly suitable due to its inherently good speed regulation and principal power factor improvement characteristics. The main drawback of the system is its complexity [5], [8], [9]. It should be mentioned that the rotor side rectifier can also be replaced by an inverter. This configuration, so called DFIM (doubly fed induction machine), is widely used in adjustable speed applications like wind power, hydro power, aerospace and naval applications [10].

One example of current frequency converters for speed control is described in [11]. In this topology, a rectifier and a converter connected by a DC-link capacitor, are connected between the grid and the motor. The speed control is attained by changing the frequency and the amplitude of the converter output voltage. However, the rectification from the grid alternating voltage to DC voltage usually causes undesired current peaks and harmonics to the power distribution network. The system also suffers from poor power factor [11], [12].

Due to the reasons mentioned above there is a desire to design a topology which can achieve speed control in a simpler manner with improved power factor meanwhile eliminating the drawbacks exposed by the speed control systems mentioned above.

In [13]-[16], a topology with a dual inverter-fed open-end winding AC motor drive is investigated. However, these motors have the stator windings open-ended and connected to the dual inverter, in contrast to the rotor windings connected to the inverter presented in this paper. Especially, the two inverters in [13] and [14] are supplied by two electrically isolated dc sources while a single dc source is applied in [15] and [16]. In addition, these dc sources have constant voltage amplitudes, unlike the dc-link capacitor in the novel topology, which has a voltage that varies according to the switching states and the current in the rotor winding.

In this paper, a novel topology described in [1] is studied. The system mainly consists of a three-phase wound-rotor induction machine and a back-to-back converter. The stator windings are directly connected to the grid while the rotor windings are connected to the converter. The speed control of the system is achieved in a simple way and with relatively good performance. An advantage of the system, compared with the conventional induction machine with short circuit rotor
windings is the highly improved power factor. The speed control and the power factor are two main issues that this paper focuses on.

II. PRINCIPLE OF OPERATION

The configuration of the system is shown in Fig. 1. In the presented configuration, the stator windings are Y-connected and directly connected to the grid. The wound rotor windings in each phase are open-ended and short-circuited via a back-to-back power electronic converter, as shown in Fig. 2. Hence, the magnetization of the induction machine can be achieved from the rotor side. The converter is mounted on the rotor (or shaft) and rotating with it. It should be noted that the system is open-loop controlled. SPWM (sinusoidal pulse width modulation) modulation strategy is applied to the two voltage source converters with the same switching frequency and modulation index. The two groups of switching signals for each converter are supplied by the dSpace control box. The phase shift between them can be varied from +180 to -180 degrees.

The operation principle of the induction machine with RPEC is illustrated by the phasor diagram shown in Fig. 3. When the induction machine is connected to the grid, the flux generated by the stator windings induces three ac voltages in the rotor windings. The rotor voltages are then rectified by the 12 diodes that are anti-parallel with the 12 valves A1-A4, B1-B4 and C1-C4, thereby charging the capacitor $C_1$ shown in Fig. 2. The capacitor voltage is then inverted by the two inverters into two groups of three-phase ac voltages, thereby introducing a phase-shift voltage vector $V'$ over the rotor windings as shown Fig. 3(b). Furthermore, voltage vector $V'$ will shift the phase of the rotor current vector $I'_r$. As rotor and stator current vectors are related to each other, the phase angle of the stator current vector will be shifted accordingly [2]. By adjusting the phase-shift angle $\theta_p$ between the two inverters, the power factor of the stator can be regulated; even the unity power factor can be achieved as shown in Fig. 3(b).

The machine is still governed by the operational principle of a conventional induction machine, thus the rotating frequency of the rotor is the difference between frequencies of the stator and the rotor currents. Therefore, speed control can be achieved by controlling the frequency of the rotor current.

III. DYNAMIC MODELING OF THE INDUCTION MACHINE WITH RPEC

This section presents the mathematical equations of the dynamic model of the induction machine with RPEC, where the rotor parameters are not transformed to the stator side.

Since the rotor windings are open-ended, the relationship $i_{sa} + i_{sr} + i_{sc} = 0$ cannot be guaranteed, which implies that the zero-sequence component of the rotor current may exist [13], [14]. Therefore the dynamic model of the induction machine with RPEC is built in the three-phase coordinate system for simplicity [17].

Take phase A as an example, the voltage equation of the stator winding A can be expressed as:

$$u_{sa} = R_s i_{sa} + \frac{d\psi_{sa}}{dt} \tag{1}$$

where:

$R_s$ - The stator resistance per phase.

$\psi_{sa}$ - $\psi_{sa} = \psi_{sa,s} + \psi_{sa,r}$ The flux linked with the stator winding A.

$\psi_{sa,s}$ - The stator flux of phase A induced by the stator current.

$\psi_{sa,r}$ - The stator flux of phase A induced by the rotor current.
The stator current generated flux \( \psi_{sa,s} \) can be derived from the currents of the stator windings as well as the mutual inductances between them.

\[
\psi_{sa,s} = L_{sa,s} \cdot i_{sa} + L_{sb,s} \cdot i_{sb} + L_{sc,s} \cdot i_{sc}
\]

\[
L_{sa,s} = L_{sm,s} + L_{sl,s}
\]

\[
L_{sb,s} = L_{sm,s} \cdot \cos\left(\frac{2\pi}{3}\right) = \frac{1}{2} L_{sm,s}
\]

\[
L_{sc,s} = L_{sm,s} \cdot \cos\left(\frac{4\pi}{3}\right) = \frac{1}{2} L_{sm,s}
\]

Substituting (3) into (2) gives

\[
\psi_{sa,s} = \left(\frac{3}{2}L_{sm,s} + L_{sl,s}\right) \cdot i_{sa} - \frac{1}{2} L_{sm,s} \cdot i_{ib} + i_{ic}.
\]

Because the stator windings are Y-connected, the sum of the stator currents is zero.

\[
i_{sa} + i_{sb} + i_{sc} = 0
\]

so (4) can be simplified to

\[
\psi_{sa,s} = L_{sa,s} \cdot i_{sa}
\]

where \( L_{sa,s} = \frac{3}{2} L_{sm,s} \).

- \( L_{sl,s} \) – The self-inductance per phase of the stator winding.
- \( L_{sm,s} \) – The leakage inductance of the stator winding.
- \( L_{sm,s} \) – The maximum value of the magnetizing inductance between the stator windings when they are in-phase.

Similarly, the flux in stator’s phase A \( \psi_{sr,a} \) generated by the currents in the rotor can be expressed by the following equation.

\[
\psi_{sr,a} = L_{sr,a} \cdot i_{ra} + L_{sr,b} \cdot i_{rb} + L_{sr,c} \cdot i_{rc}
\]

The values of the mutual inductances depend on the rotor position.

\[
\begin{align*}
L_{sa,ra} &= L_{w} \cdot \cos(\theta) \\
L_{sa,rb} &= L_{w} \cdot \cos(\theta + \frac{2\pi}{3}) \\
L_{sa,rc} &= L_{w} \cdot \cos(\theta - \frac{2\pi}{3})
\end{align*}
\]

\( L_{w} \) – The maximum value of the mutual inductance between a stator winding and a rotor winding when their axes are collinear.

\( \theta \) – The electrical angle between the stator and rotor windings of the same phase.

Inserting (8) into (7) gives

\[
\psi_{sa,r} = L_{sa,a} \cdot \cos(\theta) + i_{rb} \cdot \cos(\theta + \frac{2\pi}{3}) + i_{rc} \cdot \cos(\theta - \frac{2\pi}{3})
\]

The complete voltage equation of stator winding of phase A is thus becomes:

\[
u_{sa} = R_{s} \cdot i_{sa} + \frac{d\psi_{sa}}{dt}
\]

\[
= R_{s} \cdot i_{sa} + \frac{d}{dt}(\psi_{sa,s} + \psi_{sa,r})
\]

\[
= R_{s} \cdot i_{sa} + L_{sa,s} \cdot \frac{di_{sa}}{dt}
\]

\[
+ L_{w} \left[ \frac{di_{ra}}{dt} \cdot \cos(\theta) + \frac{di_{rb}}{dt} \cdot \cos(\theta + \frac{2\pi}{3}) + \frac{di_{rc}}{dt} \cdot \cos(\theta - \frac{2\pi}{3}) \right]
\]

\[
- \omega_{r} L_{w} \left[ i_{ra} \cdot \sin(\theta) + i_{rb} \cdot \sin(\theta + \frac{2\pi}{3}) + i_{rc} \cdot \sin(\theta - \frac{2\pi}{3}) \right]
\]

In a similar manner, the rotor voltage can be derived.

\[
u_{ra} = R_{r} \cdot i_{ra} + \frac{d}{dt}(L_{ra} + L_{rm}) \cdot \frac{di_{ra}}{dt} - \frac{1}{2} L_{ra} \cdot \frac{di_{rb}}{dt} - \frac{1}{2} L_{ra} \cdot \frac{di_{rc}}{dt}
\]

\[
+ L_{w} \left[ \frac{di_{ra}}{dt} \cdot \cos(\theta) + \frac{di_{rb}}{dt} \cdot \cos(\theta + \frac{2\pi}{3}) + \frac{di_{rc}}{dt} \cdot \cos(\theta - \frac{2\pi}{3}) \right]
\]

\[
- \omega_{r} L_{w} \left[ i_{ra} \cdot \sin(\theta + \frac{2\pi}{3}) + i_{rb} \cdot \sin(\theta - \frac{2\pi}{3}) + i_{rc} \cdot \sin(\theta - \frac{2\pi}{3}) \right]
\]

\[
R_{r} \quad \text{– The rotor resistance per phase.}
\]

\[
L_{rm} \quad \text{– The leakage inductance per phase of the rotor winding.}
\]

\[
L_{rm} \quad \text{– The maximum value of the magnetizing inductance between rotor windings when they are in-phase.}
\]

By comparing (10) and (11), it can be noted that the stator and rotor voltage equations are slightly different in form. The reason is that \( i_{sa} + i_{sb} + i_{sc} \neq 0 \) and the simplification from (4) to (6) is not feasible on the rotor side.

The complete electrical dynamics for the stator and rotor including the other two phases are listed in Appendix.

Additionally, relationships between the rotor voltages and the capacitor voltage can be expressed as:

\[
\begin{align*}
u_{ra} &= - \text{sign}(i_{ra}) \cdot k_{a} \cdot u_{c} \\
u_{rb} &= - \text{sign}(i_{rb}) \cdot k_{b} \cdot u_{c} \\
u_{rc} &= - \text{sign}(i_{rc}) \cdot k_{c} \cdot u_{c}
\end{align*}
\]

(12)

The capacitor voltage can be expressed by the rotor currents

\[
u_{c} = \frac{1}{C} \int i_{c} \, dt = \frac{1}{C} \int (k_{a} \cdot i_{ra} + k_{b} \cdot i_{rb} + k_{c} \cdot i_{rc}) \, dt
\]

(13)

where \( k_{a} \), \( k_{b} \), and \( k_{c} \) are functions of the switching states of the valves and directions of the rotor currents.

The mechanical dynamic of the system is given by (14).

\[
T_{e} - T_{\text{load}} = J \frac{d\omega}{dt}
\]

(14)

where

\( J \) – The total moment of inertia of the induction machine.

\( T_{\text{load}} \) – The load torque.

The generated electromagnetic torque \( T_{e} \) is denoted using the stator and rotor currents as shown in (15).
\[ T_e = p \cdot \left[ i_x \right] \frac{dL_x(\theta)}{d\theta} \left[ i_x \right] = -p \cdot L_x(i_x \cdot i_x + i_x \cdot i_x + i_x \cdot i_x) \sin \theta + (i_x \cdot i_x + i_x \cdot i_x + i_x \cdot i_x) \sin(\theta + \frac{2\pi}{3}) + (i_x \cdot i_x + i_x \cdot i_x + i_x \cdot i_x) \sin(\theta - \frac{2\pi}{3}) \]  

(15)

\( p \) – The number of pole pairs.

IV. EXPERIMENTAL SETUP AND RESULTS

The dynamic performance of the system was verified in the laboratory on a 1.8kW induction machine with the data shown in Table I. Since the rotor windings of the induction machine in the laboratory are already Y-connected, while the stator windings are open-ended, the machine is connected in inverted configuration. Hence, the stator windings are connected to the back-to-back converter while the rotor windings are connected to the grid. However, the windings connected to the grid are still denoted as stator and those to the converter as rotor in order to align with the concept of the configuration. The experimental setup is shown in Fig. 4.

A. Starting Transient

The machine is started without any load attached and with \( \theta_{ps} = 0^\circ \), which means that the rotor windings of the machine are short-circuited and the machine behaves as a conventional induction machine. At \( t=30s \), the load torque is applied and at \( t=56s \) \( \theta_{ps} \) is set to 180°.

The measurements, including speed, capacitor voltage and currents of stator and rotor are illustrated in Fig. 5.

When the machine starts at \( t=5s \) with \( \theta_{ps} = 0^\circ \), the starting currents of the stator and the rotor reach their peaks, 26A and 11.4A respectively. As can be seen from Fig. 5 (b), at the same time, the capacitor \( C_1 \) is charged to 220V. This is because of the so-called `dead-time', i.e., for very short period of time all switches, in one leg, are placed in off state and the rotor currents flow through the diodes that are anti-parallel with IGBTs. At around \( t=8s \), the speed gets stabilized. Since the machine is not loaded and only needs to overcome friction, the rotor has low current with the frequency 0.33Hz. Thus, the rotor speed is constant, close to the synchronous speed, as shown in Fig. 5(a). Once the speed of the machine gets stabilized, the voltage \( u_{c_1} \) begins to decline because the charging current from the rotor gets lower. The capacitor is discharged through the resistors paralleled with \( C_1 \), which is installed due to the safety precaution.

At \( t=30s \), the load torque is applied by manually tuning the field current of the DC machine. Therefore the load is increased gradually and the rotor speed has decreased to 1380 rpm accordingly. At the same time, the stator and rotor currents flow through the diodes that are anti-parallel with IGBTs. At around \( t=8s \), the speed gets stabilized. Since the machine is not loaded and only needs to overcome friction, the rotor has low current with the frequency 0.33Hz. Thus, the rotor speed is constant, close to the synchronous speed, as shown in Fig. 5(a). Once the speed of the machine gets stabilized, the voltage \( u_{c_1} \) begins to decline because the charging current from the rotor gets lower. The capacitor is discharged through the resistors paralleled with \( C_1 \), which is installed due to the safety precaution.

At \( t=56s \), \( \theta_{ps} \) is set to 180°, then the capacitor voltage \( u_{c_1} \) drops quickly to 11V. This is because the rotor currents flow through IGBTs and the capacitor is thus discharged. At this

<table>
<thead>
<tr>
<th>( p_N ) (kW)</th>
<th>( n_n ) (rpm)</th>
<th>( U_{d-c} ) (V)</th>
<th>( I_x ) (A)</th>
<th>( f_i ) (Hz)</th>
<th>( R_x ) (Ω)</th>
<th>( X_x ) (Ω)</th>
<th>( N_i / N_r )</th>
<th>( \text{pf} )</th>
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<td>380</td>
<td>4.5</td>
<td>50</td>
<td>2.3</td>
<td>1.481</td>
<td></td>
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<table>
<thead>
<tr>
<th>( U_{d-c} ) (V)</th>
<th>( I_x ) (A)</th>
<th>( R_x ) (Ω)</th>
<th>( X_x ) (Ω)</th>
<th>( X_s ) (Ω)</th>
<th>( N_i / N_r )</th>
<th>( \text{pf} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>10</td>
<td>0.8</td>
<td>1.481</td>
<td>14.7</td>
<td>380/180</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Fig. 4. View of the experimental setup in the lab (a) induction machine coupled with DC generator, (b) connection of the two converters and (c) power supply, dSpace controller and measurement unit.
stage, the voltages over the rotor windings have built up and the frequency of the rotor current is controlled by the back-to-back converter, which in turn controls the rotor speed to 1400rpm, seen in Fig. 5(a). Furthermore, after $\theta_p$ is increased to 180°, the induction machine is partly magnetized from the rotor side, thus the stator current is decreased a little.

B. Harmonic spectrum of the stator and rotor Currents

In order to obtain a harmonic spectrum, ten cycles of the stator current are analyzed using the FFT-analyze tool, shown in Fig. 6. As can be seen, the stator current has some sideband harmonics, of which the most significant components are 7.8% and 3.86% at 30Hz and 70Hz respectively. The total harmonic distortion of $i_{sa}$ is 1.96%. Besides, the measured stator current contains more harmonic components, particularly at 5$^\text{th}$ and 7$^\text{th}$ of the fundamental frequency, seen in Fig. 6.

FFT analysis was conducted for the measured rotor current, shown in Fig. 7. It can be seen that the harmonics mainly exist at 3$^\text{rd}$, 5$^\text{th}$, 7$^\text{th}$, 29$^\text{th}$ and 87$^\text{th}$ orders of the fundamental frequency of rotor current, of which the most significant one is 8.65% at 3$^\text{rd}$ of the fundamental frequency, as can be seen in Fig. 7. The harmonic distortion is 12.61%, too high to be neglected.
C. Power factor as a function of load

Fig. 8 shows the stator power factor as a function of the load torque. As can be seen, the stator power factor increases with increasing load when the rotor windings are short-circuited. Once the back-to-back converter is connected with \( \theta_{ps} \) non-zero, a phase-shift voltage will be introduced over the rotor windings thereby improving the power factor, which can be observed in Fig. 8. Specifically, larger \( \theta_{ps} \) gives higher power factor when the load torque is higher than 3Nm.

\[
\begin{align*}
\text{APPENDIX} \\
\text{Electrical dynamics of the stator in three phases:} \\
 u_{sa} &= R_s \cdot i_{sa} + L_s \frac{di_{sa}}{dt} \\
 &+ L_m \left[ \frac{di_{sb}}{dt} \cos \theta + \frac{di_{sc}}{dt} \cos \left( \theta + \frac{2\pi}{3} \right) + \frac{di_{sc}}{dt} \cos \left( \theta - \frac{2\pi}{3} \right) \right] \\
&- \omega_L L_m \left[ i_{sa} \sin \theta + i_{sb} \sin \left( \theta + \frac{2\pi}{3} \right) + i_{sc} \sin \left( \theta - \frac{2\pi}{3} \right) \right] \\
 u_{sb} &= R_s \cdot i_{sb} + L_s \frac{di_{sb}}{dt} \\
 &+ L_m \left[ \frac{di_{sa}}{dt} \cos \theta + \frac{di_{sc}}{dt} \cos \left( \theta + \frac{2\pi}{3} \right) + \frac{di_{sc}}{dt} \cos \left( \theta - \frac{2\pi}{3} \right) \right] \\
&- \omega_L L_m \left[ i_{sa} \sin \theta + i_{sb} \sin \left( \theta + \frac{2\pi}{3} \right) + i_{sc} \sin \left( \theta - \frac{2\pi}{3} \right) \right] \\
 u_{sc} &= R_s \cdot i_{sc} + L_s \frac{di_{sc}}{dt} \\
 &+ L_m \left[ \frac{di_{sa}}{dt} \cos \left( \theta - \frac{2\pi}{3} \right) + \frac{di_{sb}}{dt} \cos \theta + \frac{di_{sb}}{dt} \cos \left( \theta + \frac{2\pi}{3} \right) \right] \\
&- \omega_L L_m \left[ i_{sa} \sin \left( \theta - \frac{2\pi}{3} \right) + i_{sb} \sin \theta + i_{sc} \sin \left( \theta + \frac{2\pi}{3} \right) \right]
\end{align*}
\]

V. CONCLUSIONS

This paper presents the dynamic model of the induction machine with RPEC. Experimental verification based on a 1.8kW induction machine is performed and the good performance predicted by theory has been verified. The speed is kept constant after the system gets stabilized by simply controlling the rotor current frequency instead of using a closed-loop speed controller. In addition, the stator power factor can be effectively improved over a wide range of load. Moreover, the capacitor voltage at steady state is quite low since it only deals with the slip power, which implies that the capacitor volume can be kept low for the same capacitance. This topology is probably attractive in low-speed direct drives with induction motors, where the inherent disadvantage of low power factor of the motor can be eliminated.

REFERENCES


