Closed Loop Speed Control of Induction Generator with Scalar-Control Inverters

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Abstract

A closed loop speed control for an induction generator is presented. The system was developed for a space vector modulation-voltage source inverter and the three-phase squirrel-cage induction generator to regulate speed and generator voltages with scalar control technique. The aim of this research was to a generated voltage with a constant speed at variable mechanical torque of prime mover. The simulation results show a good performance of the system can be achieved by the proposed speed controller.

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Selection and peer-review under responsibility of COE of Sustainable Energy System, Rajamangala University of Technology Thanyaburi (RMUTT)

Keywords: Induction generator; speed control; scalar control; voltage source inverter

1. Introduction

Nowadays, a three-phase squirrel-cage induction machine operated as induction generator has widely recognized [1]. The use of induction generators has been gaining importance on the exploitation renewable energy system such as wind energy, mini/micro hydro, biomass and solar energy etc. The induction generators has many advantages over the DC generators and the synchronous generator for example: robust and brushless (squirrel-cage rotor), construction, ruggedness, ease of maintenance, absence of DC power supply for field excitation, reduce unit cost and size, better transient performance, self-protection against short-circuits and large overload, etc [2]-[5]. However, the major drawback of

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induction generator are reactive power consumption and relatively poor voltage and frequency regulation under varying prime mover speed, excitation capacitor and load characteristics [6],[7].

Fig. 1 shows the self excited induction generator (SEIG) system. When an induction machine is driven at a speed above the synchronous speed, with an external prime mover, the direction of induced torque is reversed and theoretically it starts working as an induction generator [8]. For its operation, the SEIG needs a reactive power which must be a suitable value of residual magnetism present in the rotor winding, which produces a small voltage, which increases the voltage, and so forth until the voltage is fully built up. The reactive power must be supplied by connecting a capacitor bank across the generator terminals [9], as shown in Fig. 1 (a), or by the battery start-up on the dc-side of voltage source inverter [10], as shown in Fig. 1 (b).

In [11] a method is proposed for accurately predicting the minimum value of capacitance necessary to initiate self-excitation with a stand-alone induction generator. It offers good steady-state and transient performance with build-up of generate voltage, and the perturbations of the terminal voltage and the stator current which result from load change. However, this technique has limitation in being computationally intensive. In [10] novel voltage controllers for stand-alone induction generator, in which PWM-VSI are used. It is able to maintain a constant voltage at the terminals of induction generator during step change in load. The controller gives well a dynamic response, robust and reliable.

This paper presents the development a closed loop speed control of an induction generator using space vector modulation technique with scalar-control voltage source inverter. The aim of this research is to a regulated rotor speed at variable mechanical torque of prime mover. The rest of this paper is arranged as follows: Section 2 gives the mathematical modeling of induction generator based on rotating reference frame. In Section 3 of this paper concerns the closed loop speed control of the system. To evaluate the performance of the proposed approach, simulation result is presented in Section 4. Finally, Section 5 concludes this paper.

![Fig. 1. Self excited induction generator system](image-url)
2. Mathematic Modeling of Induction Generator

The $dq$-axis equivalent circuits of the induction machine in the rotating reference frame are shown in Fig. 2. The advantage of the $dq$-axis model is its capacity to analyze the dynamic and steady state condition, giving the complete solution of any machine dynamics [12].

\[
\begin{align*}
\dot{v}_{sd} &= \frac{d}{dt}v_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} + L_{jm} \frac{di_{mq}}{dt} + \frac{1}{s} (w_e - w_r)L_m (R_r + pL_s) i_{rd} + \frac{1}{s} (w_e - w_r)L_r \frac{di_{rd}}{dt} + R_r i_{rd} \\
\dot{v}_{sq} &= \frac{d}{dt}v_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + L_{jm} \frac{di_{md}}{dt} + \frac{1}{s} (w_e - w_r)L_m (R_r + pL_s) i_{rq} + \frac{1}{s} (w_e - w_r)L_r \frac{di_{rq}}{dt} + R_r i_{rq}
\end{align*}
\]

where $v_{sd}, v_{sq}$ are the stator voltages, $i_{sd}, i_{sq}$ are the stator currents, $i_{rd}, i_{rq}$ are the rotor currents, $R_s, R_r$ are the stator and rotor resistances, $L_s, L_r$ are the stator and rotor self inductances, $L_m$ are the rotor self inductances, and $L_{jm}$ is the mutual inductances, $w_e, w_r$ are the synchronous and rotor angular speed (expressed in electrical rad/s), $p$ is the differential operator, and $d, q$ subscripts were used to represent $dq$-axis.
The stator and rotor flux-linkage components are given by

\[
\begin{bmatrix}
\frac{\dot{\psi}_{sd}}{\psi_{sd}} \\
\frac{\dot{\psi}_{sq}}{\psi_{sq}} \\
\frac{\dot{\psi}_{rd}}{\psi_{rd}} \\
\frac{\dot{\psi}_{rq}}{\psi_{rq}}
\end{bmatrix} =
\begin{bmatrix}
0 & L_m & 0 & 0 \\
0 & 0 & 0 & L_m \\
0 & L_r & 0 & 0 \\
0 & 0 & L_r & 0
\end{bmatrix}
\begin{bmatrix}
\frac{\dot{L}_{sd}}{L_{sd}} \\
\frac{\dot{L}_{sq}}{L_{sq}} \\
\frac{\dot{L}_{rd}}{L_{rd}} \\
\frac{\dot{L}_{rq}}{L_{rq}}
\end{bmatrix}
\]

(2)

where \( \psi_{sd}, \psi_{sq} \) are the stator flux-linkages, \( \psi_{rd}, \psi_{rq} \) are the rotor flux-linkages.

The stator and rotor current components can be expressed as a function of the flux-linkage components:

\[
\begin{bmatrix}
\frac{\dot{L}_{sd}}{L_{sd}} \\
\frac{\dot{L}_{sq}}{L_{sq}} \\
\frac{\dot{L}_{rd}}{L_{rd}} \\
\frac{\dot{L}_{rq}}{L_{rq}}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\frac{\dot{L}_{sd}}{L_{sd}} \\
\frac{\dot{L}_{sq}}{L_{sq}} \\
\frac{\dot{L}_{rd}}{L_{rd}} \\
\frac{\dot{L}_{rq}}{L_{rq}}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{\dot{L}_{sd}}{L_{sd}} \\
\frac{\dot{L}_{sq}}{L_{sq}} \\
\frac{\dot{L}_{rd}}{L_{rd}} \\
\frac{\dot{L}_{rq}}{L_{rq}}
\end{bmatrix} =
\begin{bmatrix}
0 & -L_m & 0 & 0 \\
0 & 0 & -L_m & 0 \\
L_r & 0 & 0 & -L_m \\
0 & L_r & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\frac{\dot{L}_{sd}}{L_{sd}} \\
\frac{\dot{L}_{sq}}{L_{sq}} \\
\frac{\dot{L}_{rd}}{L_{rd}} \\
\frac{\dot{L}_{rq}}{L_{rq}}
\end{bmatrix}
\]

(3)

where \( L_s = \frac{1}{L_s L_r - L_m^2} \).

The electromagnetic torque of induction generator \( T_e \) can be expressed by flux linkages and stator currents as well. By mathematical manipulations, several expressions for the torque can be obtained. The developed electromagnetic torque is given by

\[
T_e = \frac{3p}{2} \left( i_{sq} \psi_{sd} - i_{sd} \psi_{sq} \right)
\]

(4)

The mechanical dynamic equation becomes

\[
T_e = J \frac{dw_{m,\text{gen}}}{dt} + B w_{m,\text{gen}} + T_L
\]

(5)

The mechanical angular speed of induction generator \( w_{m,\text{gen}} \) can be determined by the mechanical dynamic equation as follows:

\[
\frac{dw_{r,\text{gen}}}{dt} = \frac{1}{J} \frac{C_p}{p} \left( T_e - T_m \right) - B w_{r,\text{gen}} \frac{\dot{w}}{\dot{w}}
\]

(6)
Therefore, the rotor speed $n_r$ can be easily found out as

$$n_{r,\text{gen}} = \frac{30w_{r,\text{gen}}}{p_p}$$

where $p_p$ is the number of poles pair, $J$ is the moment of inertia, $B$ is the viscous coefficient, $T_m$ is the prime mover torque and $w_{r,\text{gen}}$ is the rotor angular speed of induction generator, $w_{r,\text{gen}} = p_p w_{m,\text{gen}}$.

The induction generator model with the given parameters will be used in the simulation.

Neglecting the losses in voltage source inverter, the power of induction generator is given by

$$P_g = -\frac{3}{2}(v_{sd}i_{sd} + v_{sq}i_{sq})$$

3. Closed Loop Speed Control of Induction Generator

3.1. Scalar Control Scheme

Constant scalar control or voltage/frequency of induction generator refers to the scheme of controlling the torque and speed by proportionally varying the voltage with supply frequency to maintain air-gap flux constant and achieve up to rated torque at any speed by controlling the slip-speed operation [14].

Fig. 3 shows the block diagram of the control scheme for the proposed system. The system consists of the power circuit (prime mover, induction generator, and voltage source inverter) and the control system. The control system has an outer-loop speed control and a PI controller that generates slip angular speed, which is added to the speed to generate the stator frequency. The voltage source inverter receives both inputs the stator voltage reference $V_s^*$ and the stator angular reference $q_s^*$, which command a three-phase sinusoidal generator by space vector modulation (SVM) in the voltage source inverter.
The generator torque can be calculated as the ratio of mechanical power to the mechanical angular speed. For scalar control, the angular speed is leading the stator angular speed. Therefore, the electromagnetic torque developed in an induction generator can be expressed [15]

\[
T_e = \frac{3V_e^2 R_s}{w_s} \frac{1}{s_{gen} \hat{R}_s + \left( R_s / s \right)^2 + \left( X_{sl} + X_{l} \right)^2}
\]

The generator will operate above the synchronous speed. Therefore, the denominator of (9) is close to unity and the torque is virtually proportional to the rotor angular frequency for constant flux. Slip of the induction generator \( s_{gen} \) is conventionally defined as

\[
s_{gen} = \frac{P_p w_{m,gen} - w_s}{w_s} = \frac{w_d}{w_s}
\]

where \( V_s \) is stator phase voltage, \( X_{sl}, X_{l} \) are stator and rotor reactance, \( s_{gen} \) is slip of the induction generator, \( w_s \) is synchronous angular speed, \( w_{m,gen} \) is mechanical generator angular speed, and \( w_d \) is slip angular speed.

Under normal condition, the slip is typically very small. In this case,

\[
\frac{R_s}{s_{gen}} \approx R_s \quad \text{and} \quad \frac{R}{s_{gen}} \approx \left( X_{sl} + X_{l} \right)
\]

Therefore, the developed torque can be approximated as

\[
T_e = \frac{3V_e^2 w_d}{w_s^2 R_s}
\]

From (12), it can be seen that the relationship between electromagnetic torque and slip angular speed if \( V_s / w_s \) is kept constant, electromagnetic torque developed could be controlled by controlling the slip angular speed.

From equivalent circuit of induction machine, which neglect stator resistance and stator inductance, and recognizing that the air gap flux can be given by

\[
y_{airgap} = \frac{V_s}{w_s}
\]

Therefore, the developed torque in term air gap flux can be approximated as

\[
T_e = \frac{3y_{airgap}^2 w_d}{R_s}
\]
From (14) is very important. It indicates that, the electromagnetic torque $T_e$ is proportional to slip angular speed $w_{sl}$ for constant flux $y_m$ operation, or electromagnetic torque $T_e$ is proportional to flux $y_m^2$ for constant slip angular speed $w_{sl}$ operation.

### 3.2. Speed Control Design

From (12), it can be deduced that to control the torque developed by generator, the slip speed needs to be controlled. An induction generator system using a PI-controller to regulate speed is illustrated in Fig. 4. The electromagnetic torque developed can be considered proportional to the slip angular speed as

$$ T_e = k_t w_{sl} \quad (15) $$

where $k_t = T_{e,\text{rated}} / w_{sl}$.

By taking Laplace transform of (6) in order determine the mechanical angular speed $w_{m,\text{gen}}$, which is the relationship between the electromagnetic torque and assume no-speed dependent damping term ($B = 0$), the mechanical angular speed is expressed as

$$ w_{m,\text{gen}} = \frac{T_e - T_m}{JS} \quad (16) $$

Fig. 4 shows the block diagram of the speed control loop. Then, the rotor angular speed reference $w_{m,\text{gen}}$ is compared with the measured rotor angular speed $w_{m,\text{gen}}$ to generate error signal. This signal is the input of the PI speed controller that computes the value of the slip angular speed reference $w_{sl}^*$. The output of PI speed controller can be expressed as

$$ w_{sl}^*(s) = \frac{k_p}{s} + \frac{k_i}{s} \cdot \frac{w_{m,\text{gen}} - w_{m,\text{gen}}^*}{s} \quad (17) $$

where $k_p$ is the propotional gain, $k_i$ is the integral gain.

From Fig. 4, the open-loop transfer function of the system assuming the prime mover torque is zero ($T_m = 0$), can be given by
The closed-loop transfer function of the speed control system can be expressed as

\[
H(s) = \frac{k_i (k_p s + k_i)}{s^2 + \frac{k_i k_p}{J} s + \frac{k k_i}{J}}
\]

(19)

The characteristic polynomial is

\[
S^2 + \frac{k_i k_p}{J} S + \frac{k k_i}{J} = 0
\]

(20)

The general form of the characteristic polynomial of a second-order system is given by

\[
S^2 + 2\zeta \omega_n S + \omega_n^2 = 0
\]

(21)

where \( \omega_n \) is the natural angular frequency for \( \zeta \leq 1 \); \( \zeta \) is the damping ratio.

The parameters of the PI controller might be calculated as

\[
k_p = \frac{2\zeta \omega_n J}{k_i}
\]

(22)

\[
k_i = \frac{\omega_n^2 J}{k_i}
\]

(23)

4. Simulation Results

The simulation in this paper has been developed in Matlab/Simulink environment. The induction generator parameters used in the simulation are given in Table 1.

Table 1. Induction generator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-phase</td>
<td>0.37 kW</td>
<td>( R_s = 30 ) W</td>
</tr>
<tr>
<td>Hz</td>
<td>50</td>
<td>( R_r = 31.49 ) W</td>
</tr>
<tr>
<td>Voltage</td>
<td>230/400 V</td>
<td>( L_s = 1.0942 ) H</td>
</tr>
<tr>
<td>Current</td>
<td>1.8/1.05 A</td>
<td>( L_r = 1.0942 ) H</td>
</tr>
<tr>
<td>Speed</td>
<td>1360 rpm</td>
<td>( n_r = 1 ) H</td>
</tr>
<tr>
<td>capacitance</td>
<td>1 H</td>
<td>( L_m = 1 ) H</td>
</tr>
</tbody>
</table>
Fig. 5 shows the simulated waveforms of the induction generator system using the open loop control scheme under the condition of the unit step torque. The prime mover generated the prime mover torque $T_m$ increase accordingly from -0.2 Nm to -2.5 Nm at $t = 0.8$ sec as shown in Fig. 5 (a). Fig. 5 (b) shows the generator electromagnetic torque $T_e$, it can be seen that the induction generator operates above synchronous speed in the generating mode, it produces a negative torque that accelerates the generator, and the rotor speed $n_{r,gen}$ increases accordingly from 1520 rpm to 1630 rpm as shown in Fig. 5 (c). The waveforms of the stator current and stator voltage, are also given in Fig. 5 (d) and (e), respectively.

Fig. 6 shows the simulated waveforms for an induction generator system using the speed control scheme. Fig. 6 (a) shows the step unit torque of prime mover is changed from -0.2 Nm to -2.5 Nm (Full rated torque) at $t = 2$ sec and then decreased to -0.2 Nm at $t = 3$ sec. It can be seen that the generator electromagnetic torque responds quickly. The rotor speed response of the control system is shown in Fig. 6 (b), and the rotor speed follows the rotor speed reference, which has a constant at 1550 rpm. Fig. 6 (c) shows the stator current, which varies with generator electromagnetic torque accordingly. In Fig. 6 (d), the stator flux is kept constant during the sudden mechanical torque of prime mover changes. It can be seen that the stator flux responds quickly while the stator current is adjusted according to keep electromagnetic generator torque constant. Fig. 6 (e) shows the trajectories of the stator flux in Fig. 6 (d) for $0 \leq t \leq 3.5$ sec.
5. Conclusion

This paper has presented a speed controller for the induction generator with scalar-control inverter. The drive response with the designed PI-controller has been successfully verified with simulation results. Satisfactory performance is observed at constant speed operation during variable mechanical torque of prime mover condition. The developed controller has a simple, fast dynamic response, reliable and robust.

Acknowledgements

The work was supported by the Faculty of Engineering, Chiang Mai University.

References


