FUZZY CONTROLLER FOR SELF-EXCITED DUAL STAR INDUCTION GENERATOR WITH ONLINE ESTIMATION OF MAGNETIZING INDUCTANCE USED IN WIND ENERGY CONVERSION

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Key words: Self-excited dual star induction generator (DSIG), Vector control, Fuzzy logic controller, Pulse width modulation (PWM) rectifiers, Magnetizing current and magnetizing inductance estimation.

Induction generator with direct field oriented control is preferred for high performance applications due to its excellent dynamic behavior. The accuracy for the dual star induction generator control in the remote area highly depends on estimating the undetectable machine parameter values, such as the magnetizing inductance and flux. The aim of this paper is to propose a novel direct rotor flux oriented control with online estimation of magnetizing current, which applied to stand alone dual star induction generator supplying a wind turbine in remote area. The induction generator is connected to nonlinear load through two PWM rectifiers. The results of the proposed technique based on the magnetizing inductance estimation that used to control of induction generator shows an importance to determine the rotor flux position.

1. INTRODUCTION

The multiphase asynchronous machine controlled by a five-leg inverter, it was first operated in 1969. Since 1990, researchers continue to improve and operate multi-phase machines in industrial applications and wind energy conversion [1].

At present, polyphase asynchronous machine introduced in several industrial and power generation applications due to its advantages. Low harmonic of both torque pulsations and rotor current, as well as minimizing both rotor losses and the phase current in the multiphase machine and power converter without increasing the phase voltage. Moreover, the machine presents a good reliability and the segmentation of controller power on more inverter legs [2–5].

In this paper, a novel control system for doubly star induction generator that uses a rotor flux orientation is presented. The performance of the control was tested for a wide ranges variation of both load and speed. The doubly star asynchronous generator supplies a variable dc load. The main goal is to remain constant both rotor flux and dc voltage.

In the asynchronous cage generator the variation of magnetizing inductance is the main factor in the dynamics of voltage build and stabilization. If we consider the magnetizing inductance constant the model of the generator generates a tension which tends towards the infinite. This is why the introduction of a magnetizing inductance estimator in the proposed control algorithm [6].

In this paper, we introduce a novel control scheme; an estimator of inductance magnetizing is introduced to vector control contrary to the traditional algorithm where the inductance magnetizing is considered constant. A comparison between two control systems has been presented.

2. MODELING OF SELF-EXCITED DOUBLY STAR ASYNCHRONOUS GENERATOR

The model of doubly star asynchronous generator is the same as the doubly star asynchronous motor. The Park model of the doubly star asynchronous generator in the reference frame at the rotating field (d, q) is represented in Fig. 1.

The DSIG contains two identical phase stator windings offset by an electrical angle $\alpha = 30^\circ$, and a squirrel cage rotor [7, 8].

![Fig. 1 – Representation of DSIG in the Park frame.](image)

The electrical model of the DSIG in the synchronous reference frame (d-q) which presented as [9–11]:

$$v_{ds1} = -n_i j_{ds1} - \sigma_x \psi_{qs1} + p \psi_{ds1}.$$ (1)

$$v_{qs1} = -n_i j_{qs1} + \sigma_x \psi_{ds1} + p \psi_{qs1}.$$ (2)
\[ v_{d1} = -r_1 i_{d1} - \omega_e \psi_{q1} + p \psi_{d1} \] (3)

\[ v_{q1} = -r_1 i_{q1} - \omega_e \psi_{d1} + p \psi_{q1} \] (4)

\[ v_{dr} = 0 = r_1 i_{dr} -(\omega_e - \omega_r) \psi_{qr} + p \psi_{dr} \] (5)

\[ v_{qr} = 0 = r_1 i_{qr} -(\omega_e - \omega_r) \psi_{dr} + p \psi_{qr} \] (6)

\[ T_{em} = \frac{3}{2} \frac{L_m}{I_{dr} + L_m} [(\psi_{q1} + i_{q1}) \psi_{dr} - (i_{d1} + i_{d2}) \psi_{qr}], \] (13)

where \( L_m \) is the magnetizing inductance.

The amplitude of the magnetizing current \( i_m \) is determined as [12]:

\[ i_m = \sqrt{(-r_{d1} - i_{d2} + i_{d})^2 + (-r_{q1} - i_{q2} + i_{q})^2} \] (14)

It must be emphasized that the generator needs residual magnetism so that the self-excitation process can be started.

The magnetizing inductance, \( L_m \) used in this work is given as follow [10,12]:

\[ L_m = 0.1406 + 0.0014 i_m - 0.0012 i_m^2 + 0.00005 i_m^3 \] (15)

### 3. VECTOR CONTROL

The goal in controlling system is to ensure dc bus voltage to its reference. This can be obtained through controlling the flux and the power transmitted by the generator.

The objective of the direct rotor field oriented control theory, which applied to the DSIG is the same direct current machine model, to separately control the torque and the flux. However, the rotor flux linkage axis is forced to align with the d-axis for the ideal field oriented control, and it follows that:

\[ \psi_{dr} = \psi_r^* \] (16)

\[ p \psi_{dr} = \psi_{qr} = 0. \] (17)

Substituting (16) and (17) into (5) and (6), yields

\[ r_1 i_{dr} + p \psi_{r} = 0 \longrightarrow i_{dr} = 0. \] (18)

\[ r_1 i_{dr} + p \psi_{r} = 0 \longrightarrow i_{qr} = -\frac{\psi_{r}^*}{r_r}, \] (19)

where \( \omega_s^* = \omega_e - \omega_r \), \( \omega_{sl} \) is the slip speed.

The rotor currents is reformulated using the terms of stator currents which divided from (11) and (12) as follows:

\[ i_{dr} = \frac{1}{(L_m + L_{dr})} \left[ \psi_{r}^* - L_m (i_{d1} + i_{d2}) \right] \] (20)

\[ i_{qr} = -\frac{1}{(L_m + L_{dr})} (i_{q1} + i_{q2}) \] (21)

Substituting (20) into (18), obtain

\[ \omega_{sl}^* = \frac{r_r L_m}{(L_m + L_{dr})} \psi_{r}^*, \] (22)
where $i_{qs1}^* + i_{qs2}^* = i_{qs}^*$. (23)

The reference power is expressed by the desired dc voltage value as follows:

$$V_{DC}^* l_{dc} = P^* = P_{ele} = T_{em} \Omega,$$  

(24)

where $\Omega$ is the angular speed of the rotor. Neglecting the losses, the torque expression can be written as:

$$T_{em} = \frac{P^*}{\Omega}.$$  

(25)

The component references of stator current and slip speed $\omega_{sl}$ can be expressed as:

$$i_{sd1}^* + i_{sd2}^* = i_{sd}.$$  

(26)

$$\tau_r = \frac{L_r}{r_r}.$$  

(27)

The implementation of the control is presented in Fig. 3.

3. MAGNETIZING INDUCTANCE ESTIMATION

The magnetizing current amplitude $|I_m|$ is related to the magnetizing inductance. Mainly, it is necessary to online estimate of the $L_m$ value during machine operation, when the generator operates under a weak flux range. By substituting expression (20) and (21) to (14) the magnetizing current can be expressed as follow:

$$i_m = \frac{1}{L_m + L_r} \left[ \frac{\psi_r - i_d (2L_m + L_r)}{[\frac{\psi_r}{L_r} - \frac{i_d}{2L_m + L_r}]} \right]^*.$$  

(30)

4. FUZZY LOGIC CONTROLLER

The principle basics of fuzzy logic controller has been introduced by Mamdani and Assilian based on Fuzzy set theory suggested by Zadeh in 1965 is that linguistic, which the imprecise knowledge of human experts is utilized [13,14]. What the stand out in the Fig. 2, is the proposed voltage fuzzy proportional integral (PI) controller block diagram. However, it has the following structure:

- two inputs: are the error and its derivate;
- one output: is the signal control.

$E$ is the voltage error given by:

$$E(k) = V_{DC}^*(k) - V_{DC}(k-1).$$  

(31)

de $E$ is derived from the voltage error approximated by:

$$dE(k) = E(k) - E(k-1).$$  

(32)

To change the sensitivity of the controller we used three gains $FE, FdE, FdU$ (scale factors), that kept the structure of the controller.

The PI corrector transfer function in discrete representation ($Z$) is written as:

$$\frac{V_{DC}^*(Z)}{E(Z)} = k_p + k_i \frac{Z}{Z-1},$$  

(34)

where $k_p$ and $k_i$ are the gains of the PI controller.

From Eq. (34) the PI equation is obtained as:

$$u(z)(1 - z^{-1}) = k_p (1 - z^{-1})E(z) + k_i E(z).$$  

(35)

By reformulating Eq. (35) which can note $dE$ and $du$ the changing of the error $E$ and the signal controller $u$ respectively, the obtained equation is given by:

$$du = k_p dE(z) + k_i E(z).$$  

(36)

From Eq. (36) it appears to keep the same inputs/output of the conventional PI for the fuzzy-PI.

Controller parameters are modified according to the perturbation which are changes. The fuzzy controller is based on three blocks:
- fuzzification,
- rules bases,
- defuzzification.

4.1 FUZZIFICATION

Inputs variables $E(k)$ and $dE(K)$ are transformed into fuzzy variables called linguistic labels. The triangular shapes of membership functions have been adapted for each label [15, 16].

The discourse universe of all inputs and output variables are established as $(-1, 1)$. The appropriate scale factors are adapted to bring the input and output variables into this discourse universe.

Figure 4 presents the membership function chosen for each input signal ($E$, $dE$).

Each discourse universe are divided for seven overlapping fuzzy sets: Positive Big (PB), Positive
Medium (PM), Positive Small (PS), Zero Environ (ZE), Negative Small (NS), Negative Medium (NM) and Negative Big (NB). Each fuzzy variable is a member of the subsets with a degree of membership $\mu$ varying between 0 (non-member) and 1 (full-member) [17].

$$\begin{align*}
\frac{1}{L_m + L_r} \left[ \left( \omega_r - 2\omega_m + \omega_c \right) i_d^* - \left( \omega_r + \omega_c \right) i_s^* \right] = L_m + L_r \frac{di_m}{dt} + L_m \frac{di_r}{dt} \\
\end{align*}$$

4.2. RULES BASES

Fuzzy logic rule database is based on a series of logical if and-then conditions. Table 1 shows the corresponding rule for the fuzzy controller, the construction of these rules is used a qualitative knowledge, deduced from several simulation tests [18]. Each variable contains 7 subsets, this leads to $7 \times 7 = 49$ rules.

**Table 1**

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4.3. DEFUZZIFICATION

This stage deals with the converting fuzzy variables to crisp variables. Moreover, the centre of gravity defuzzification method is adopted. The Mamdani inference algorithm has introduced to our system [18,19]. The output function is presented as:

$$u_f = \frac{\sum_{k=1}^{n} u_f(k) \mu(u_f(k))}{\sum_{k=1}^{n} \mu(u_f(k))}$$

where $n$ is the total number of rule; $\mu(u_f(k))$ is the output membership value for $k^{th}$ rule.

5. INTERPRETATION OF RESULTS

This section presents simulations results of the proposed control technique that has been implemented using Matlab/Simulink. The sampling time used: $T_s = 50 \mu s$. Parameters of DSIG are $r_{1,2} = 1.9 \, \Omega$, $r_r = 2.9 \, \Omega$, $L_{l1,2} = 0.0132 \, H$, $L_{d} = 0.0132 \, H$ and $L_{m} = 0.011 \, H$.

Figure 5 presents the dc bus voltage where its reference is set at 1100 V. What stands out in this figure is the dc bus voltage is perfectly controlled to its reference with the proposed control technique that used the $L_m$ estimator. Meanwhile, the dc bus voltage cannot follow its reference,
when the rotor speed changes to the low value. Furthermore, it is clear from Fig. 5 that the conventional control scheme without $L_m$ estimator is not suitable to achieve the desired dc voltage which is not robust under operating of a high variations of rotor speed and load condition.

During the simulation the system has been exposed to a speed and load variation to see the response of the control. These variations can be seen in Fig. 6. One of the remarkable results is shown in Fig. 7 which is the stator current follows the controlled current. Neglecting the estimation of magnetizing inductance in vector control can reduced of its performances, this effect is clearly shown in Fig. 8.

Figure 9 represents stator voltage and current for both stars (1 and 2), the second star is shifted by an electrical angle $\alpha = 30^\circ$ regarding to the first star. In Fig. 10, the stator phase current is shown to be successfully maintained within the imposed hysteresis band limits under different load condition, where the fixed current band ‘h’ is set to 0.5 A.

Figure 11 represents that the rotor flux $\psi_r$ is constant during entire operation with the proposed control. Other ways, under the conventional control, the rotor flux cannot follows its reference when the machine operate under low rotor speed condition. As can see on Fig. 12 that the error between the real magnetizing inductance and its estimated is low than 0.01 of its value.
6. CONCLUSION

This paper has been presented a rotor flux oriented control based on the fuzzy logic, which has been applied to self-excited dual star induction generator under a variable speed wind system, have been presented and studied. Ignoring an estimation of magnetizing inductance in field oriented vector control of doubly star induction generator, can lead to detuned steady state operation. The proposed control provides a well DC voltage control with near sinusoidal stator current and low harmonic. The proposed system conversion control can be exploited in the wind power generation.

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