T-S 퍼지 외란 관측기를 이용한 IPMSM의 강인 제어

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ABSTRACT
To improve the control performance of the IPMSM, a novel nonlinear disturbance observer is proposed by using the T-S fuzzy model. A T-S fuzzy model is the combination of local linear models considered at each operating point. Usually the inverse model is easy to obtain in linear systems but not in nonlinear systems. To design a nonlinear disturbance observer, a nonlinear inverse model is obtained based on nonlinear inverse model which is the fuzzy combination of the local linear inverse models. The proposed DOB is used with a PDC controller which is one of the T-S fuzzy controller, and its performance improvement is shown from the simulation results.

Keywords: Nonlinear Disturbance Observer, Interior Permanent Magnet Synchronous Motors, T-S Fuzzy Model, PDC Controller
I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are widely used in various applications, such as electric vehicles and spindle motors under the field oriented control technique, with many advantages such as maintenance-free operation, high controllability, robustness against the environment, high efficiency and high power factor operation. There are Surface PMSM (SPMSM) and Interior PMSM (IPMSM) [1].

A SPMSM can be considered as a linear system with the zero d-axis current. However, in the case of IPMSM, to obtain the maximum torque per ampere (MTPA) [2], its d-axis current must be controlled as nonzero reference, and this makes it difficult to control [3-6]. With the nonzero d-axis current, the dynamic of IPMSM is nonlinear and nonlinear control methods are required.

One of the effective nonlinear control method is T-S fuzzy control [7-11]. And to improve the robustness by eliminating the effect of disturbances, the use of disturbance observer (DOB) is desirable. The DOB based on the inverse model of the controlled plant have many research results and applications [12-15, 18, 19]. Usually, this kind of DOBs are designed for linear systems since the inverse models are obtained easily from transfer functions [20]. In nonlinear systems, the inverse system can be obtained under the very limited condition.

In this paper, for the robust control of IPMSM, a novel DOB is proposed based on the T-S fuzzy model, which is the convex combination of local linear models in the state space [11]. An inverse system of IPMSM is obtained as a convex combination of the local linear inverse systems [16, 20]. The existence condition of an inverse system in the state space is to have a input direct through matrix D, however most systems including IPMSM have no such a matrix. To overcome this difficulty, a filter, which has a derivative and a low pass filter, is proposed in this paper [19]. A basic T-S fuzzy PDC controller is used with nonlinear DOB and simulation results shows the disturbance decoupling using the proposed DOB [13, 17].

II. BACKGROUND OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTORS

The following IPMSM model is considered.

\[
\begin{align*}
L_q \frac{di_q}{dt} &= V_q - R_i q - p W_i L_q i_d - p W_q \Phi_f \\
L_d \frac{di_d}{dt} &= V_d - R_i d + p W_i L_{dq} \\
J_m \frac{dW_r}{dt} &= 3p \frac{\Phi_f i_q + (L_d - L_q) i_d}{2} - B_m W_r - T_l
\end{align*}
\]

(1)

where \( V_d \) and \( V_q \) are d-q axis stator voltages, \( i_d \) and \( i_q \) are d-q axis stator currents, \( L_d \) and \( L_q \) are d-q axis stator inductances, \( R \) is a stator resistance, \( \Phi_f \) is the rotor magnetic flux, \( T_l \) is a load torques, \( J_m \) is the moment of inertia, \( B_m \) is friction coefficient, and \( p \) is the number of poles.

The MTPA can be achieved by differentiating Eq.(1) with respect to q-axis current \( i_q \) and setting the resulting equation to zero, which gives in [6]:

\[
i_d = \frac{\Psi_f}{2(L_q - L_d)} - \sqrt{\frac{\Psi_f^2}{4(L_q - L_d)^2} + i_q^2}
\]

(2)

Substituting Eq.(2) into Eq.(1), one can get a nonlinear relationship between \( i_d \) and \( T_e \) as:

\[
T_e = \frac{3p}{2} \left( \frac{\Psi_f i_q - \Psi_f i_d}{2} - (L_d - L_q) \right) \left( \frac{\Psi_f^2 i_q^2}{4(L_q - L_d)^2} + i_q^4 \right)
\]

(3)

In real time, the implementation of the drive system becomes potentially undefined and computationally burdensome with expressions Eq.(2) and Eq.(3).

To address this, the d-axis and q-axis currents are obtained by expanding the square root term of Eq.(2) via a Taylor series expansion about zero.
III. TAKAGI–SUGENO FUZZY CONTROLLER FOR IPMSM

The design procedure described in this paper begins with the so-called Takagi–Sugeno fuzzy model, in which local linear models of a nonlinear system are combined by fuzzy IF-THEN rules [7].

The i-th rules of the T-S fuzzy models are of the following form.

Model rule i:

\[
\text{IF } z_1(t) \text{ is } M_{i1} \text{ and } \ldots \text{ and } z_p(t) \text{ is } M_{ip} \\
\text{THEN } x(t) = A_i x(t) + B_i u(t) \\
y(t) = C_i x(t) \quad i = 1,2,\ldots, r
\]  

(4)

where \(M_{ij}\) is the fuzzy set and \(r\) is the number of rules; \(x(t) \in \mathbb{R}^n\) is the state vector, \(u(t) \in \mathbb{R}^m\) is the input vector, \(y(t) \in \mathbb{R}^q\) is the output vector, \(A_i \in \mathbb{R}^{nxn}\), \(B_i \in \mathbb{R}^{nxm}\), and \(C_i \in \mathbb{R}^{qxn}\) are the parameters of local linear models, \(z_1(t), \ldots, z_p(t)\). are known premise variables that may be functions of the state variables. We will use \(z(t)\) to denote the vector containing all the individual elements \(z_1(t), \ldots, z_p(t)\). It is assumed in this paper that the premise variables are not functions of the input variables \(u(t)\). This assumption is needed to avoid a complicated defuzzification process of fuzzy controllers.

Given a pair of \((x(t),u(t))\), the final T-S fuzzy model is inferred as follows:

\[
\dot{x}(t) = \sum_{i=1}^{r} w_i(z(t)) \left( A_i x(t) + B_i u(t) \right) \\
y(t) = \sum_{i=1}^{r} w_i(z(t)) \left( C_i x(t) \right)
\]

(5)

for all \(t\). The term \(M_i(z(t))\) is the grade of membership of \(z_i(t)\) in \(M_i\). Since

\[
\sum_{i=1}^{r} w_i(z(t)) > 0, \\
\sum_{i=1}^{r} w_i(z(t)) \geq 0, \quad i = 1,2,\ldots, r
\]

(7)

We have

\[
\sum_{i=1}^{r} h_i(z(t)) = 1, \\
h_{i}(z(t)) \geq 0, \quad i = 1,2,\ldots, r \quad \text{for all } t
\]

(8)

The stability of T-S fuzzy controller is determined based on the Lyapunov stability which can be applicable for a regulator problem.

To change the tracking problem into a regulator problem, an error model is derived as follows. The reference input is determined from the following steady state equation:

\[
v_{q_{\text{ref}}} - R_{i_{q_{\text{ref}}}} = -p W_{r_{\text{ref}}} L_d d - p W_{r_{\text{ref}}} \Psi_f = 0 \\
v_{d_{\text{ref}}} - R_{i_{d_{\text{ref}}}} = -p W_{r_{\text{ref}}} L_q q = 0 \\
\frac{3P}{2} (\Psi_f i_{q_{\text{ref}}} + (L_d - L_q) i_d i_{q_{\text{ref}}}) - B_m W_{r_{\text{ref}}} - T_i = 0
\]

(9)

Note that variable \(i_d\) and \(i_q\) are still shown in Eq.(1) and they are also included in the reference voltages.

With the reference input currents, the d-axis and q-axis voltages of error model are determined as: By substituting the above Eq.(9) into Eq.(1) the error model is obtained as:

\[
\begin{align*}
\frac{de_{i_d}}{dt} &= v_{q_{\text{ref}}} - R e_{i_d} - pe_{i_q} \Psi_f - v_{d_{\text{ref}}} + pe_{i_q} L_d e_{i_d} \\
\frac{de_{i_q}}{dt} &= v_{d_{\text{ref}}} - R e_{i_q} + pe_{i_d} L_q e_{i_q} \\
\frac{de_{W_i}}{dt} &= \frac{3P}{2} (\Psi_f e_{i_q} + (L_d - L_q) i_d e_{i_q}) - B_m e_{W_i} - T_i
\end{align*}
\]

(10)
where
\[ v_q = v_{q_{\text{ref}}} + v_{q_{\text{ref}}} \quad \text{and} \quad v_d = v_{d_{\text{ref}}} + v_{d_{\text{ref}}} \quad (11) \]

The above dynamics have simple nonlinear terms but difficult to be used for the design of DOB without T-S fuzzy approximation. For some constant values of \( i_d(t), i_q(t) \), the system can be linear. If \( i_q(t), i_d(t) \) are chosen as the premise variables, the following T-S fuzzy model of IPMSM is obtained:
\[
\dot{x}(t) = \sum_{i=1}^{n} \mu_i(w) A_i x(t) + B_i u(t)
\]
\[ y(t) = C x(t) \quad (12) \]

where \( \mu_i(w) \) is a membership function and

\[
x(t) = \begin{bmatrix} e_q(t) \\ e_d(t) \\ e_{w_q}(t) \end{bmatrix}, \quad A_i = \begin{bmatrix} 0 & 0 & -p_{L_d} & -p_{i_d} \\ -R & 0 & -L_q & L_i \\ 0 & -R' & 0 & -L_i \\ \frac{3p}{2} (i_q + (L_d - L_i) i_d) & J_m & 0 & -B_m \end{bmatrix}, \quad B_i = \begin{bmatrix} 1 \\ \frac{1}{L_q} \\ 0 \\ \frac{1}{L_d} \end{bmatrix} \]

and \( A_i \) and \( B_i \) are for \( i \)-th local linear model.

Note that the parameter \( C \) can be determined as the desired value since the all states of IPMSM are usually measurable for the field oriented control.

Various type of T-S fuzzy controller can be used with the proposed DOB, however, in this paper, the most basic T-S fuzzy PDC controller, which does not consider any robustness, is used to show the disturbance decoupling of the proposed DOB.

A PDC controller has the following form:
\[ u(t) = -\sum_{j=1}^{m} \mu_j P_j x(t) \quad (13) \]

where \( P_i \) are calculated from the LMI.

The known load disturbances can be considered in the reference input, however unknown disturbance must considered by using disturbance observer. In the next section, a novel nonlinear DOB based on T-S fuzzy inverse system is proposed.

IV. T-S FUZZY DISTURBANCE OBSERVER FOR IPMSM

In this chapter, an inverse nonlinear system is derived and used for the design of a nonlinear DOB. The inverse systems have been studied by using transfer functions only for linear systems but seldom for the nonlinear systems\[14,17\].

The following figure shows the basic concept of DOB in linear system using the transfer function.

\[ \text{Fig. 1 The block diagram of DOB} \]

In the Fig.1, \( u_r \) is the input of controller, \( u \) is the input after compensation, \( d \) is the unknown external disturbance, \( P(s) \) is the original plant, \( P_n^{-1}(s) \) is the useful inverse system of it.

The inverse system is obtained very easily from the transfer function and the problem is solved using the low pass filter under the condition of low frequency input and disturbances. However this approach is impossible in nonlinear systems. so, the following inverse T-S fuzzy model in the state space is proposed in this paper.

The i-th local linear system is described in the state space as follows:
\[
\dot{x}(t) = A_i x(t) + B_i u(t) \\
y(t) = C_i x(t) + D_i u(t)
\]

(14)

Under the assumption of existence of nonsingular D, its inverse system is obtained as follows:

\[
\dot{x}(i, inw) = A_{i, inw} x(t) + B_{i, inw} u(t) \\
y(i, inw) = C_{i, inw} x(t) + D_{i, inw} u(t)
\]

(15)

where

\[
A_{i, inw} = A_i - B_i D_i^{-1} C_i, B_{i, inw} = B_i D_i^{-1}, C_{i, inw} = -D_i^{-1} C_i
\]

\[D_{i, inw} = D_i^{-1}\]

For the above local inverse systems, a T-S fuzzy inverse exists if \(B = B_i, C = C_i\) and \(D = D_i\). In IPMSM, \(B_i\) and \(C_i\) are constant but D does not exist, then the inverse systems cannot be derived.

In this paper, to make an inverse system available, a special filter is proposed for the output.

\[
y(i, inw) = Q(s) G_{LPF}(s) y(t)
\]

(16)

where \(Q(s)\) is the polynomial function of \(s\) and its output has the D matrix, and \(G_{LPF}(s)\) is a low pass filter.

Suppose inputs and disturbances are low frequency signals and their outputs are not depend on the low-pass filter and the filtered output is considered as follows.

\[
y(i, new) = Q(s) y(t)
\]

(17)

The role of \(Q(s)\) is to make \(y(i, new)\) as the sum of derivatives of \(y(t)\) and change the system to have the nonsingular matrix D in the state space.

In this paper, \(Q(s)\) is given as \((ps+q)\) for the IPMSM and its usage is explained as follows: for the inputs and disturbances which are not high frequencies, the low pass filter can be neglected and the \(y(i, new)\) can be described as follows:

\[
y(i, new) = p y_i(t) + q y(t) \\
= C_{i, new} x(t) + D_{i, new} u(t)
\]

(18)

As a result, the inverse system of the IPMSM can be derived as follows:

\[
\dot{x}(i, inw) = \sum_{i=1}^{n} \mu_i(w) \{ A_i x(t) + B_i u(t) \} \\
y(i, new) = \sum_{i=1}^{n} \mu_i(w) \{ C_{i, new} x(t) + D_{i, new} u(t) \}
\]

(19)

Now the inverse system is the convex combination of local linear inverse systems and the overall stability is guaranteed by the stability of each local inverse system.

The stability of i-th local inverse system is described as a Hurwitz matrix as follows:

\[
A_i x(t) - B_i D_i^{-1} C_i = -D_i^{-1} C_i
\]

(21)

Note that the IPMSM has simple T-S fuzzy model and its inverse system easy to obtain, however, without T-S fuzzy model this kind approach is impossible.

\[
C_{i, inw} = a C_i A_i + b I_{\infty}, \quad D_{i, inw} = a C_i B_i
\]

(22)

Combining the DOB system with error system we built, we can get the overall system as a nonlinear DOB using T-S fuzzy model for IPMSM.

\[
\begin{array}{c}
\text{DOB system} \\
\text{Error system}
\end{array}
\]

Fig. 2 Block diagram of nonlinear DOB
In next chapter, we will introduce a simulation to illustrate the performance of DOB applied to IPMSM.

V. SIMULATION RESULT

In the previous chapters, we mainly proposed a T-S fuzzy control method with the disturbance observer (DOB) based on the inverse system for IPMSM. Simulation results for IPMSM will be shown with the proposed method.

The parameters of the IPMSM, used in the simulation, are given in the following table:

<table>
<thead>
<tr>
<th>Pole pair number P</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>d-axis inductance Ld</td>
<td>42.44[mH]</td>
</tr>
<tr>
<td>q-axis inductance Lq</td>
<td>79.57[mH]</td>
</tr>
<tr>
<td>Stator resistance R</td>
<td>1.93[Ω]</td>
</tr>
<tr>
<td>Motor inertia Jm</td>
<td>0.003[Kgm]</td>
</tr>
<tr>
<td>Friction coefficient Bm</td>
<td>0.001[Nm/rad/sec]</td>
</tr>
<tr>
<td>Flux constant Ψf</td>
<td>0.311[Volts/rad/sec]</td>
</tr>
</tbody>
</table>

The parameters of the local linear models:

\[
A_1 = \begin{bmatrix} -24.2554 & 0 & 2.8503 \\ 682.3000 & 0 & -0.3333 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 12.5676 \\ 0 \end{bmatrix}
\]

\[
A_2 = \begin{bmatrix} -24.2554 & 0 & -23.8180 \\ -245.950 & 0 & -0.3333 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 12.5676 \\ 0 \end{bmatrix}
\]

\[
A_3 = \begin{bmatrix} -24.2554 & 0 & 2.8503 \\ 682.3000 & 0 & -0.3333 \end{bmatrix}, \quad B_3 = \begin{bmatrix} 12.5676 \\ 0 \end{bmatrix}
\]

\[
A_4 = \begin{bmatrix} -24.2554 & 0 & -23.8180 \\ -245.950 & 0 & -0.3333 \end{bmatrix}, \quad B_4 = \begin{bmatrix} 12.5676 \\ 0 \end{bmatrix}
\]

The PDC controller gains F:

\[
F_1 = \begin{bmatrix} -1.9035 & 21.8083 & 54.5174 \\ -11.6318 & -1.9159 & -0.0000 \end{bmatrix}
\]

\[
F_2 = \begin{bmatrix} -1.9035 & -3.4394 & -21.4654 \\ 1.8345 & -1.9159 & 0.0000 \end{bmatrix}
\]

\[
F_3 = \begin{bmatrix} -1.9035 & 934.4644 & 54.5174 \\ -498.4123 & -1.9159 & 4.7742 \end{bmatrix}
\]

\[
F_4 = \begin{bmatrix} -1.9035 & 1270.20 & -21.4654 \\ -677.50 & -1.9159 & 4.7742 \end{bmatrix}
\]
The parameters of the inverse system models:

\[
A_{1_{\omega}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \\
B_{1_{\omega}} = \begin{bmatrix} 12.5676 & 0 \\ 0 & 23.5627 \\ 0 & 0 \end{bmatrix}, \\
A_{2_{\omega}} = \begin{bmatrix} 0 & 0 & 0 \\ -245.950 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \\
B_{2_{\omega}} = \begin{bmatrix} 12.5676 & 0 \\ 0 & 23.5627 \\ 0 & 0 \end{bmatrix}, \\
A_{3_{\omega}} = \begin{bmatrix} 0 & 0 & 0 \\ 682.3000 & 0 & -0.3333 \\ 0 & 0 & 0 \end{bmatrix}, \\
B_{3_{\omega}} = \begin{bmatrix} 12.5676 & 0 \\ 0 & 23.5627 \\ 0 & 0 \end{bmatrix}, \\
A_{4_{\omega}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -245.950 & 0 & -0.3333 \end{bmatrix}, \\
B_{4_{\omega}} = \begin{bmatrix} 12.5676 & 0 \\ 0 & 23.5627 \\ 0 & 0 \end{bmatrix}
\]

Two cases will be considered. The first one is control plant without DOB, and the second is with DOB. Through the comparison between the above two cases, the performance of DOB can be checked apparently.

The simulation results of the first are shown in the following figure.

In the speed control, the reference speed is \( w_{r-ref} = 300 \) rad/sec and some sinusoidal signals will be applied on the plant as the unmeasured disturbance. Due to the disturbance, the output \( w \) fluctuates at 280 rad/sec and can not achieve the desired tracking performance.

With the reference speed \( w_{r-ref} = 300 \) rad/sec and some sinusoidal disturbance, the q-axis current \( i_q \) behaves as the above figure. In the Fig. 7, \( i_q \) fluctuates periodically with the period of sinusoidal disturbance.
With the reference speed $w_{ref} = 300$ rad/sec and some sinusoidal disturbance, the $d$-axis voltage $v_d$ is changed from 300V to 0V and at 11s the response fluctuates because of the disturbance.

From the above simulation results, without the DOB, the plant can not have a good performance to against the disturbance and shows the deteriorated stability and control performances.

The simulation results of the case 2 are shown in the following figure.

In order to make a comparation, here we still set the reference speed $w_{ref} = 300$ rad/sec and the same desired sinusoidal signals. We can see even there exists a disturbance, after applying a DOB to the system, the system can realize the tracking performance, the value of $w$ will tend to be steady to 300 rad/sec without any fluctuation as simulation time goes.
With the reference speed $w_{ref} = 300$ rad/sec and some sinusoidal disturbance, the $d$-axis current $i_d$ is as the above Fig. 11. We can tell that $i_d$ tends to be the desired value.

![Graph of dq-axis current](image)

**Fig. 12** q-axis current $i_q$ under the case 2

With the reference speed $w_{ref} = 300$ rad/sec and some sinusoidal disturbance, the $q$-axis current $i_q$ tends to be desired value.

![Graph of dq-axis voltage](image)

**Fig. 13** $v_d$ of LMI fuzzy controlled system under the case 2

With the reference speed $w_{ref} = 300$ rad/sec and sinusoidal disturbance, even there still exists disturbance, after we build a DOB, it can make a compensation to deteriorate the negative effect of disturbance. And the waveform will range from 300 to 0 and finally tend to be a steady state.

![Graph of dq-axis voltage](image)

**Fig. 14** $v_q$ of LMI fuzzy controlled system under the case 2

With the reference speed $w_{ref} = 300$ rad/sec and sinusoidal disturbance, the $q$-axis voltage $v_q$ tends to be steady at 200V shown as the above Fig. 14.

Through the comparisons, the effectiveness of the proposed DOB is shown clearly.

### VI. CONCLUSIONS

The T-S fuzzy inverse model of IPMSM is derived by using the T-S fuzzy model, which is the convex combination of local linear inverse system in the state space. Using the inverse model, the nonlinear DOB is proposed and used with the PDC controller. The effectiveness of the proposed DOB has been shown through the computer simulation comparing the IPMSM system with DOB to the one without DOB.

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