Robustness of Adaptive Fuzzy for PMSM Sensorless Speed Controller

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Abstract—**This paper has presented an adaptive fuzzy controller for permanent magnet synchronous motor. A rotor speed estimation based on sliding mode observer. Space-vector pulse width modulation was used for slipping frequency vector control system. The simulation architecture of system was implemented on Modelsim and Matlab/Simulink. The algorithm controls have implemented by very high speed integrated circuit hardware description language and embedded to Simulink/Matlab for controlling. The simulation results shown that the motor's speed has good performance and isn't sensitive to the parameter variations. Controller integrated in an IC saves space and avoids the influence of external factors preferred as noise or temperature.**

Index Terms—**fpga, adaptive fuzzy controller, vhdl, modelsim, simulink, sliding mode control, co-simulation**

I. INTRODUCTION

To cope with many uncertainties, such as noise, external load, fiction force etc which affect to the performance quality of motor, many intelligent control techniques such as fuzzy, neural network, sliding mode observer (SMO), extended kalman filter have been developed. They helped to control exactly position of motor [1], [2]

This paper follows a previously published paper [3], where the fuzzy and SMO algorithm have been studied and successfully simulated. This article applied new mechanism for adjusting the knowledge base of fuzzy controller (FC). The contents are organized as follows. Firstly, the mathematical model of permanent magnet synchronous motor (PMSM) and adaptive fuzzy controller (AFC) were designed and derived. Secondly, the SMO algorithm was introduced. Finally, the simulation setups and results are described.

II. THE DESIGN FOR PMSM DRIVE

A. Mathematical Model of PMSM

$$\frac{di_d}{dt} = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_r i_q \tag{1}$$

$$\frac{di_q}{dt} = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q - \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda p\omega_r}{L_q} \tag{2}$$

In which: L_q, L_d are the inductance on q and d axis; R is the resistance of the stator windings; i_q, i_d are the current on q and d axis; V_q, V_d are the voltage on q and d axis; λ is the permanent magnet flux linkage; p is a number of pole pairs; ω_r is the rotational speed of the rotor.

The current loop control of PMSM drive in Fig. 1 is based on a vector control approach. Three phases current were being feedback and through vector control structure, enabling controlling current $i_d \approx 0$, helped controlling three phase motor similar to a one phase motor.

B. Speed Controller Design

The speed controller (SP) in Fig. 1 presented the structure of an adaptive fuzzy PI controller and reference model (RM). The detailed description is as follows:

The typical second order system was used for RM: [4]

$$\frac{\omega_m(s)}{\omega_r^*(s)} = \frac{\omega_n^2}{s^2 + 2\omega_n(s) + \omega_n^2} \tag{3}$$

Using the bilinear transformation, we have discrete function in z domain and difference equation:

$$\frac{\omega_m(z^{-1})}{\omega_r^*(z^{-1})} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}} \tag{4}$$

With coefficients: a_0=0.000098, a_1=0.000196, a_2=0.000098, b_1=-1.96039, b_2=0.9608

The FC was composed of four elements (Fig. 2). Based on singleton fuzzifier, the fuzzification (FI) converted controller inputs (e and de) into information that the inference mechanism can easily use to activate and apply

rules. An inference mechanism emulated the expert's decision making in interpreting and applying knowledge about how best to control the speed of PMSM. A knowledge base contained a fuzzy logic quantification of the expert's linguistic description of how to achieve good control (a set of If-Then rules). A defuzzification (DFI) based on product-inference rule and central average defuzzifier method to convert the conclusions of the inference mechanism into actual inputs for the PI process.
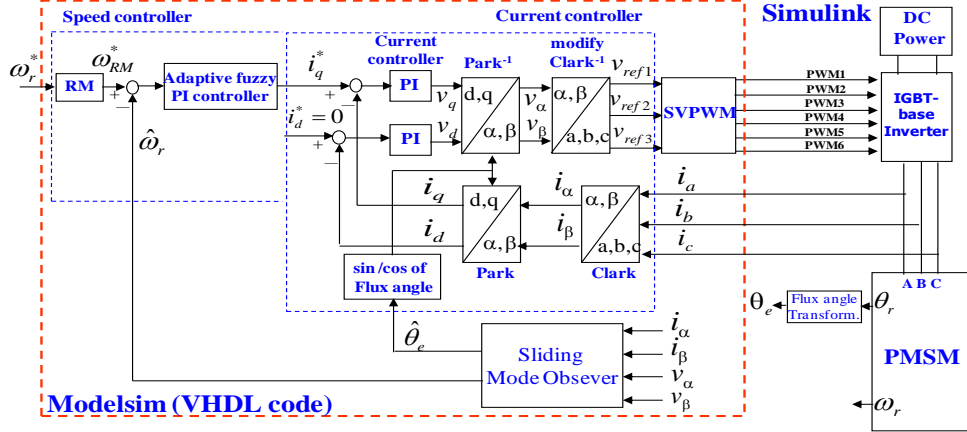

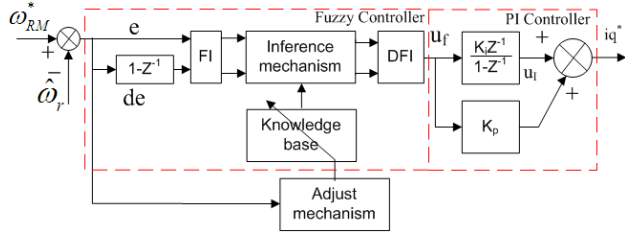Figure 1. Block diagram of PMSM's controller

Figure 2. Structure of Adaptive fuzzy PI controller

The input linguist values of FC:

$$e(k) = \omega_{RM}^*(k) - \hat{\omega}_r(k) \qquad (5)$$

$$de(k) = e(k) - e(k-1) \qquad (6)$$

Membership function has shape of symmetrical triangle (Fig. 3) and controlling rules have form:

If e was A_m and de was B_n then u_f was $C_{m,n}$ (7)

Crisp value in the output of FC:

$$u_f(e, de) = \frac{\sum_{n=i}^{i+1}\sum_{m=j}^{j+1} c_{m,n}[\mu_{A_n}(e) * \mu_{B_n}(de)]}{\sum_{n=i}^{i+1}\sum_{m=j}^{j+1}[\mu_{A_n}(e) * \mu_{B_n}(de)]} \approx \sum_{n=i}^{i+1}\sum_{m=j}^{j+1} c_{m,n} d_{n,m} \qquad (8)$$

In which $c_{m,n}\, d_{n,m}$ is adjusting parameters for FC.

After successful designing FC, the adjust mechanism was added to FC, so the FC becomes AFC. The error speed between estimated rotor speed ($\hat{\omega}_r$) and output of RM (ω_{RM}^*) was supplied to adjust mechanism. When motor run in heavy or light load condition, the error speed increased, the adaptive feature of system stimulated and changed Knowledge Base of FC. With this Adjusting Mechanism, motor can keep a balance speed in case load changed. Using the method of gradient descent determines the adaptive control law for the system: [5]

Definition of instantaneous value function:

$$J(k+1) = \frac{1}{2}[e(k+1)]^2 = \frac{1}{2}[\omega_{RM}^*(k+1) - \hat{\omega}_r(k+1)]^2 \,(9)$$

Parameters $c_{m,n}$ was determined by variation of the instantaneous value function

$$\Delta c_{m,n}(k+1) = -\alpha \frac{\partial J(k+1)}{\partial c_{m,n}(k)} \qquad (10)$$

In which: α shows the adaptive rate of the system

Laplace and bilinear transform of electromagnetic torque with considering the mechanical load, we had discrete function in Z domain of PMSM motor

$$\frac{\hat{\omega}_r(k)}{i_q^*(k)} = \frac{K_t}{F} \frac{(1 - e^{\frac{-FT_s}{J_m}})z^{-1}}{1 - e^{\frac{-FT_s}{J_m}} z^{-1}} \qquad (11)$$

In which T_s is sampling time, z-1 is a stage of delay time

Relationship between i_q^* current and output of SP block was described by the equation:

$$i_q^*(k) = u_i(k-1) + K_p u_f(k) + K_i u_f(k-1) \quad (12)$$

In which K_p, K_i are the gain of PI controller; u_f is output value of AFC.
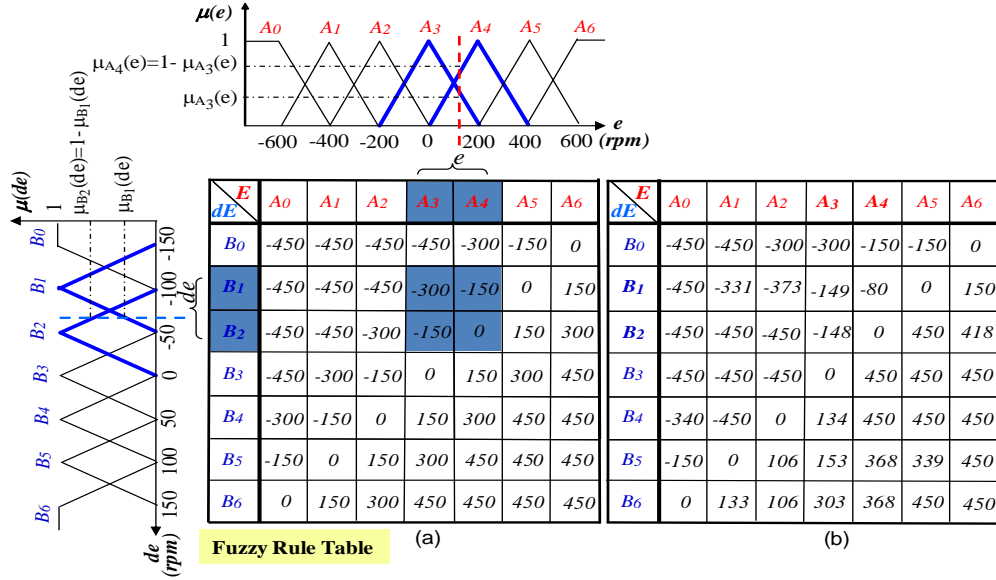
From equation (11) and (12), we obtained the relationship between motor speed and output functions of the FC:

$$\hat{\omega}_r(k) = \Phi \hat{\omega}_r(k-1) + u_i(k-2)\gamma + K_p\gamma u_f(k-1) + K_i\gamma u_f(k-2) \qquad (13)$$

In which: $\Phi = e^{\frac{-FT}{J_m}}$, $\gamma = \frac{K_t(1-\Phi)}{F}$

Variation of the instantaneous value function $J(k+1)$ from equation number (9) was:

$$\frac{\partial J(k+1)}{\partial C_{m,n}(k)} = -\frac{\alpha e(k-1)(\partial \hat{\omega}_r(k+1))}{\partial u_f(k)} \frac{\partial u_f(k)}{\partial C_{m,n}(k)} \quad (14)$$

E\dE	A0	A1	A2	A3	A4	A5	A6
B0	-450	-450	-450	-450	-300	-150	0
B1	-450	-450	-450	-300	-150	0	150
B2	-450	-450	-300	-150	0	150	300
B3	-450	-300	-150	0	150	300	450
B4	-300	-150	0	150	300	450	450
B5	-150	0	150	300	450	450	450
B6	0	150	300	450	450	450	450

E\dE	A0	A1	A2	A3	A4	A5	A6
B0	-450	-450	-300	-300	-150	-150	0
B1	-450	-331	-373	-149	-80	0	150
B2	-450	-450	-450	-148	0	450	418
B3	-450	-450	-450	0	450	450	450
B4	-340	-450	0	134	450	450	450
B5	-150	0	106	153	368	339	450
B6	0	133	106	303	368	450	450

Fuzzy Rule Table (a)   (b)

Figure 3.   The initial values of FC (a) and the adjusted values at *t*=0.3s, speed command =1000rpm, heavy load condition (b)

Therefore, the parameters of the FC could be adjusted through the function

$$\Delta C_{m,n}(k) = \alpha(K_p e(k) + K_i e(k-1))\gamma d_{m,n}$$
$$\approx \alpha(K_p e(k) + K_i e(k-1)) Sign(\gamma) d_{m,n} \quad (15)$$

C. Sliding Mode Observer:

SMO block in Fig. 1 constructed by a sliding mode observer, a bang-bang controller, two low-pass filters and a rotor flux angle (FA) computation was shown in Fig.4.
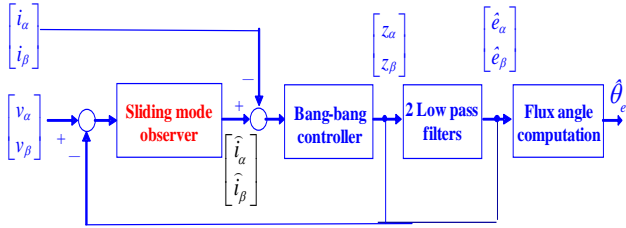

Figure 4.   Rotor FA estimation based on SMO

The equation of PMSM on the $\alpha - \beta$:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} r_s + sL & 0 \\ 0 & r_s + sL \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \omega_e K_E \begin{bmatrix} -\sin\theta_e \\ \cos\theta_e \end{bmatrix} \quad (16)$$

where $[v_\alpha\ v_\beta]^T$ and $[i_\alpha\ i_\beta]^T$ are voltage on fixed coordinate and current on fixed coordinate, respectively; L is the inductance of the d-axis or q axis; θ_e is rotor FA; s is the differential operator.

From (16), the EMF developed is calculated as

$$e = \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \underline{\triangleq} \omega_e K_E \begin{bmatrix} -\sin\theta_e \\ \cos\theta_e \end{bmatrix} \quad (17)$$

And the SMO is designed by

$$\frac{d}{dt}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} = \begin{bmatrix} -r_s/L & 0 \\ 0 & -r_s/L \end{bmatrix}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} + \frac{1}{L}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} - \frac{1}{L}\begin{bmatrix} z_\alpha \\ z_\beta \end{bmatrix} \quad (18)$$

The discrete equation of (18) is:

$$\begin{bmatrix} \hat{i}_\alpha(n+1) \\ \hat{i}_\beta(n+1) \end{bmatrix} = \begin{bmatrix} \sigma & 0 \\ 0 & \sigma \end{bmatrix}\begin{bmatrix} \hat{i}_\alpha(n) \\ \hat{i}_\beta(n) \end{bmatrix} + \psi\begin{bmatrix} v_\alpha(n) \\ v_\beta(n) \end{bmatrix} - \psi\begin{bmatrix} \hat{e}_\alpha(n) \\ \hat{e}_\beta(n) \end{bmatrix} \quad (19)$$

We use $[\hat{e}_\alpha\ \hat{e}_\beta]^T$ instead of $[z_\alpha\ z_\beta]^T$ as the feedback value in SMO; $\sigma \approx \frac{Ts}{L}$, $\psi \approx 1 - T_s\frac{r_s}{L}$ and $[\hat{i}_\alpha\ \hat{i}_\beta]^T$ is the estimated current on fixed coordinate.

$$Z = \begin{bmatrix} z_\alpha \\ z_\beta \end{bmatrix} \underline{\triangleq} k * sign\left(\begin{bmatrix} \hat{i}_\alpha - i_\alpha \\ \hat{i}_\beta - i_\beta \end{bmatrix}\right) \quad (20)$$

where the current error is defined by $e_{cur} \underline{\triangleq} [\tilde{i}_\alpha\ \ \tilde{i}_\beta]^T = [\hat{i}_\alpha - i_\alpha\ \ \hat{i}_\beta - i_\beta]^T$. If k is large enough, the inequality in (21) can be satisfied and the SMO can enter into sliding mode condition.

$$e_{cur}^T \dot{e}_{cur} < 0 \quad (21)$$

Therefore, it generates the results of $e_{cur} = \dot{e}_{cur} = 0$. The back-EMF will be:

$$\begin{bmatrix} z_\alpha \\ z_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \omega_e K_E \begin{bmatrix} -\sin\theta_e \\ \cos\theta_e \end{bmatrix} \quad (22)$$

To alleviate the high frequency in bang-bang control, two low-pass filters are applied to create smoother back-EMF signal:

$$\hat{e}_\alpha = \frac{2\pi f_0}{s + 2\pi f_0} z_\alpha \quad (23)$$

Finally, the rotor FA ($\hat{\theta}_e$) can be computed by

$$\hat{\theta}_e(n) = \tan^{-1}\left(-\frac{\hat{e}_\alpha(n)}{\hat{e}_\beta(n)}\right) \quad (24)$$
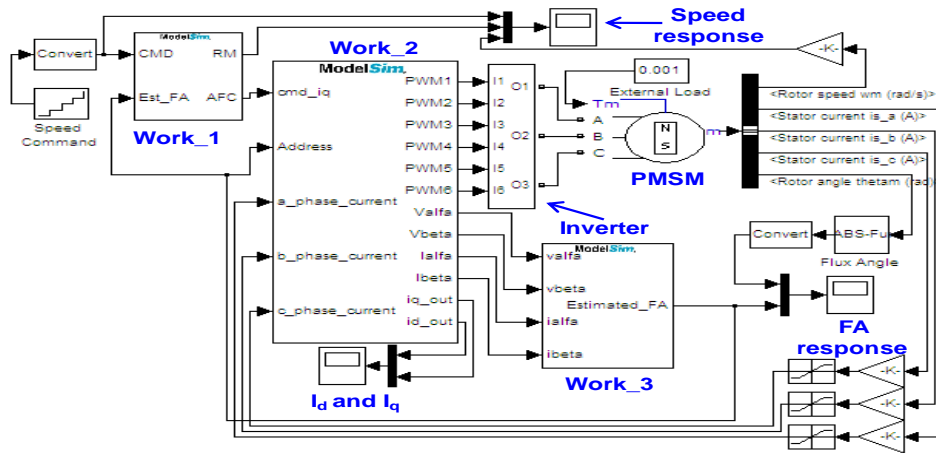
Figure 5.   Co-Simulation model on Simulink/Matlab

III.   SIMULATION SETUPS AND SIMULATION RESULTS

The co-simulation architecture for AFC sensorless speed control system is shown in Fig. 5. The SimPowerSystem blockset in the Simulink executed the PMSM and the inverter. The EDA simulator link for ModelSim executed the co-simulation using very high speed integrated circuit hardware description language (VHDL) code running in ModelSim program. VHDL code of SP block in Fig. 1 (RM, inference mechanism, knowledge base, adjust mechanism, PI controller, FI and DFI) were embedded to Work_1 (Fig. 5); VHDL code of Clark, Park, Clark^{-1} and Park^{-1} transform; two PI controllers (for controlling the i_d and i_q) and Space-vector pulse width modulation (SVPWM) in Fig. 1 were embedded to Work_2 (Fig. 5). VHDL code of sliding mode observer was embedded to Work_3 (Fig. 5). Some scopes were using for displaying speed responses; i_d/i_q current and rotor FA response. The adaptive rate was set to 0.5 and initial values of FC were shown in Fig. 3a.

In the simulation of the rotor FA estimation, sensorless speed control is considered at normal load condition. The estimated rotor FA was feed-backed to the current loop for vector control and to the speed loop for speed control. The simulation work of the step speed response was tested. The motor speeds command is designed with step varying from 0rpm→ 1500rpm. The simulation results for the actual rotor FA (θ_e), the estimated FA angle ($\hat{\theta}_e$) are shown in Fig. 7. It presented that the estimated rotor FA can follows the actual rotor FA without delay time. The results for actual rotor speed response with different load condition are shown in Fig.6 and Fig.8. When the system parameters were changed to double load condition, the FC was used and the actual rotor speed cannot follow the desired speed (Fig. 6). In Fig. 8 showed the speed response when AFC was used and Fig. 8a showed at normal load condition, Fig.8b showed at double load condition. The adjust mechanism produces a compensation signal by using (15) which was modified the knowledge base of the FC to force the system to behave like the RM. Although the load condition was changed two times, the rotor speed still tracked the desired speed well (Fig. 8a). The rising time and steady-

state value are about 0.1s and near 0mm, which presents a good speed following desired speed with a little overshoot occurred.

The FPGA (Altera) resource usage of speed controller, current control and SMO block in Fig.5 were 5093 Logic Elements (LEs) and 0RAM bits, 2,657 LEs and 49,152 RAM bits, 2630 Les and 49152 RAM bits; respectively. The designed PMSM's parameters are listed in Table I. The parameters of controllers are shown in Table II.

Compared with the rotor FA and speed response from [3], the proposed method has the advantage of better accuracy to follow the actual rotor FA and desired speed under both normal and heavy load condition. The rotor speed can run faster and the rotor FA at high speed response can reduce the oscillation.

Finally, the simulation results shown in Figs. 6~8 demonstrate the effectiveness and correctness of the sensorless speed control for PMSM.
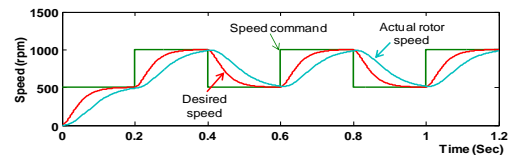

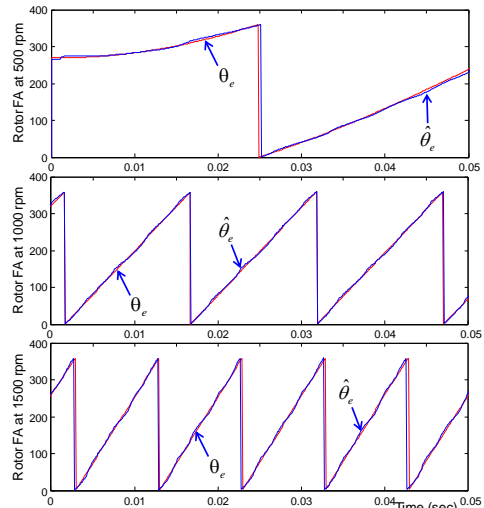Figure 6 Speed response with FC was used at double load condition

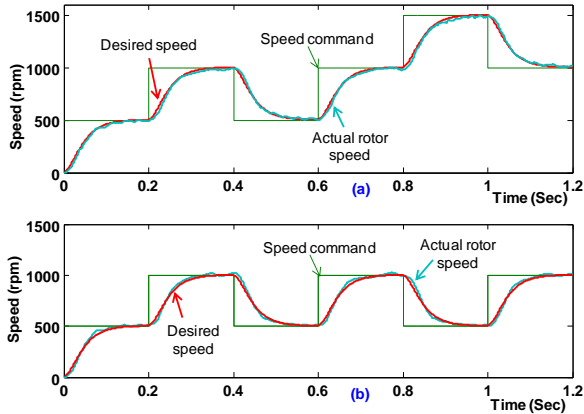Figure 7.   Actual rotor FA (θ_e) and estimated rotor FA ($\hat{\theta}_e$)

Figure 8. Speed response with AFC was used at normal load condition (a) and at double load condition (b)

TABLE I. PARAMETERS OF PMSM

Parameters	Values
Stator resistor	R=1.3Ω
Stator inductance	L=6.3mH
Pole pairs	P=4
Inertia	J=0.000108 kg*m^2
Friction factor	F=0.0013 N*m*s
Voltage constant	V=52.2 V_peak/1000rpm
Torque constant	K_t=0.43169 N.m/A_peak

TABLE II. PARAMETERS OF CONTROLLERS

Parameters		Values (Q15)
Speed controller	Ki	70
	Kp	10000
i_d controller	Kid	150
	Kpd	1000
i_q controller	Kiq	300
	Kpq	2000
SMO	K	1938
	f_0	314

IV. CONCLUSION

Adaptive fuzzy and sensorless control techniques were successfully demonstrated in this article. The system separate to three parts, the vector control is used to decouple the nonlinear characteristics of PMSM, the AFC is designed to cope with the dynamic uncertainty effect, the SMO is applied to estimate the rotor FA without using sensor. All functionalities based on hardware design have been integrated in one FPGA chip. The performance of system was validated by co-simulation results. The paper has been demonstrated to be the best tracking rotor speed under different external load condition.

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