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Research Article

Fuzzy Adaptive Internal Model control for the speed regulation of a Permanent Magnet Synchronous motor with an Index matrix converter

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Abstract

In this paper we design a fuzzy adaptive internal model control for the speed varying problem of a PMSM. The PMSM under the vector control model is studied. The designing of the fuzzy adaptive IMC involves three steps. First a standard internal model controller is designed. This model has high input saturation. A modified IMC is designed which reduces the input saturation. The variation of inertia at the load end is reduced by designing a Fuzzy based adaptive IMC. An Indirect Matrix Converter is provided at the power supply end for the better controllability of the speed regulation of the PMSM.

Keywords: *Permanent Magnet Synchronous Motor, Index Matrix Converter, Fuzzy Adaptive Control, Internal Model Controller*

1. Introduction

Permanent magnet synchronous motor is a widely used industrial motor. Its advantageous features like such as the high efficiency, high power density and torque to inertia ratio, allows it to be chosen for most of the applications. The control of a PMSM is a non-linear control system. This complicates the application of any of the linear control algorithms and obtaining a high performance using linear algorithms is quite difficult.

Interior model control (IMC) technique was presented by Garcia and Morari (C. E. Garcia and M. Morari *Ind. Eng. Chem. Process Des. Develop.*, 1982) and afterward was under escalated exploration also improvement throughout the previous decades (M. Morari and E. Zafirarious, 1989; Rivals and Z. L. Personna *IEEE Trans. Neural Netw*, 2000). The IMC strategy incorporates an internal model and an internal model controller which comprises of the reverse internal model and a filter. It has great capabilities of tracking, disturbance rejection and robustness. It additionally gives a compelling system to the investigation of control framework execution, particularly for the security what's more heartiness issues(C. E. Garcia and M. Morari *Ind. Eng. Chem. Process Des. Develop.*, 1982; Rivals and Z. L. Personna *IEEE Trans. Neural Netw*, 2000). Around these effects, diverse sorts of displaying routines about IMC have been produced, counting customary arithmetic modelling (C. E. Garcia and M. Morari *Ind. Eng. Chem. Process Des. Develop.*, 1982; M. Morari and E. Zafirious *Robust Process Control*., 1989; Rivals and Z. L. Personna *IEEE Trans. Neural Netw*, 2000), neural network modelling (W. F. Xie and A. B. Rad *IEEE Trans. Ind. Electron*, 2000), fuzzy modelling (Q. Zhang and E. A. Zafirious *IEEE Trans. Autom. Control*, 1989), volterra series modelling (G. Horn, J. R. Arulandu, and R. D. Braatz *Ind. Eng. Chem. Res.*, 1996),and so on. Various methods have been proposed to improve the performance of a Internal Model Control scheme. In this paper we study the different types of Internal Model Control Schemes. First, a first order IMC is designed based on the reference quadrature current. Separate PI controllers are provided for each of the current loops. The disturbance rejection and the tracking of this model is week, and there is input saturation. To improve the disturbance rejection, a modified IMC is designed which has an additional filter (G. Stephanopoulos and H. P. Huang *Chem. Eng. Sci*, 1986). This improves the tracking and reduces the input saturation. There is constant variation of inertia at the load end of the system. Continuous variation of inertia at the load end leads to the degrading performance of the control loop. In order to reduce the inertia variation, two laws are implemented, a linear adaptive law and a fuzzy adaptive law. The linear adaptive law is a straight forward method but due to the saturation that is involved in this system, it may not represent the relationship between the control parameters involved and the varying inertia. So, a fuzzy adaptive law is used. In this method, the estimation of the varying inertia is taken and the fuzzy adaptive laws are built based on previously held experimental results. This allows the controller to be tuned automatically to the varying speed, identifying the inertia at that point. The related simulation and experimental results are given.

The PMSM is used in servo systems for the reason that its speed is exactly proportional to the input frequency. An AC-AC converter like a Matrix converter with no power

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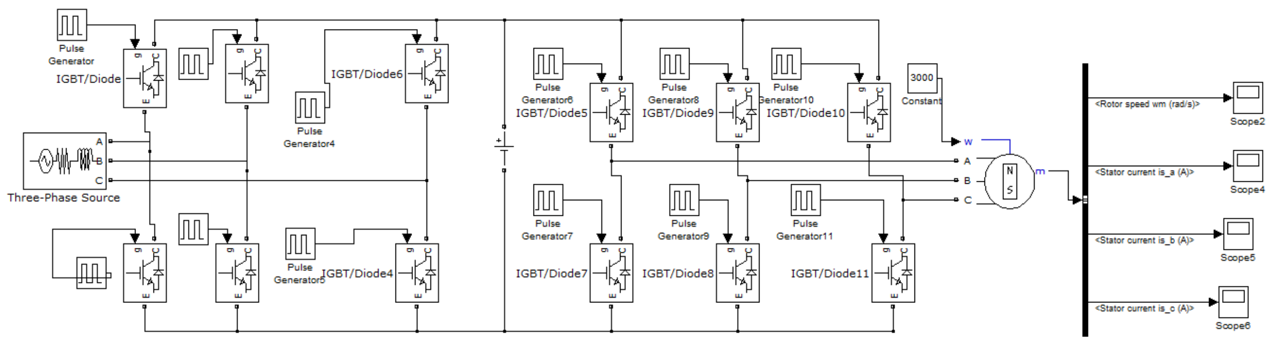

Fig 1. MATLAB simulation of Indirect Matrix Converter using IGBT

storage component can be used to provide the PMSM with a good frequency input. Matrix converters are of two types, direct matrix converters and Indirect Matrix converters. The indirect matrix converter similar to a frequency converter, only that it the former has six bidirectional switches in its inverter stage.

2. Indirect matrix converter

There are two stages in an Indirect Matrix Converter. First there is a rectifier stage and then there is an inverter stage. Pulse width modulation technique is use in the rectifier stage and Space Vector Pulse Width Modulation technique is used in the inverter stage. Isolated Gate Bipolar Transistors (IGBT) are used to build the Indirect Matrix Converter circuit. IGBTs are devices used in power electronics circuits. It is a three terminal device, whose primary application is being used as a switching device.

The construction of an IGBT is similar to that of a vertical n-channel MOSFET except that the n+ channel of the MOSFET is replaced with a P+ collector in the IGBT. Its primary feature is fast switching. It is in applications wherever pulse width modulation is required. It combines the simple GATE drive characteristics of a MOSFET with the high current and low saturation voltage capability of a bipolar transistor. It combines an isolated gate FET for control input and a bipolar power transistor as a switch in a single device. Here is a MATLAB simulation of a Index matrix converter built using IGBTs, The above simulation is built for obtaining a three phase output. The simulation output are given below.

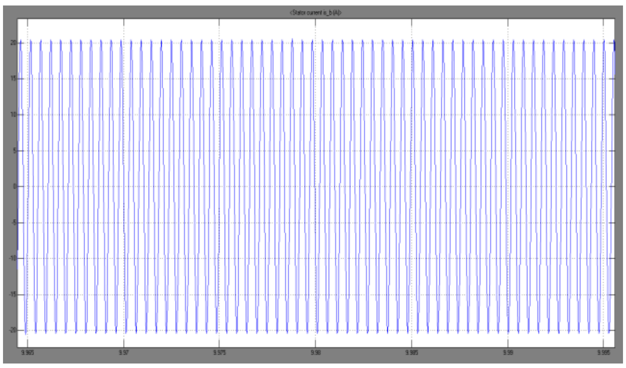

Fig 2. Simulation output graph of phase A from the indirect matrix converter.

The fig 2 shows the current output is a pure sinusoidal wave. Output shown here is only from the A phase line. All the three phase lines, A, B, and C, have a 120^o between each other. The speed (fig 3) output from the given output can be observed as to be a constant from the same given. From these outputs switching capability and the efficiency to work at high frequency with low current saturation allows IGBT devices to be well suited in PMSM motor vector control drives.

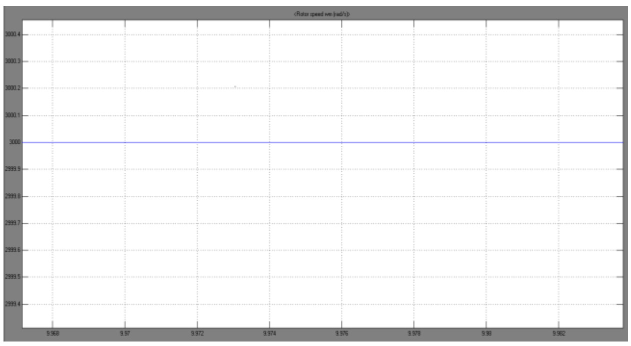

Fig 3. Speed response of the PMSM with indirect matrix converter.

From these results we can say that the Indirect Matrix converter provides a better signal for the effective performance of the PMSM motor. This power supply circuit provides a better frequency response that enables the PMSM to have a better speed response.

3. Internal model control

An Internal model control scheme consists of an internal model of the system and an internal model controller which has the inverse of the system and a filter. The Internal Model Control Scheme has good tracking, disturbance rejection and provides an effective framework for the analysis of the control systems performance which helps on improving the stability and the robustness.

3.1. Equations

Let us consider the d-q co-ordinate of the PMSM (P. C. Krause *Analysis of ElectricMachinery*, 1995). The mathematical model of the co-ordinate can be represented by the following equation.

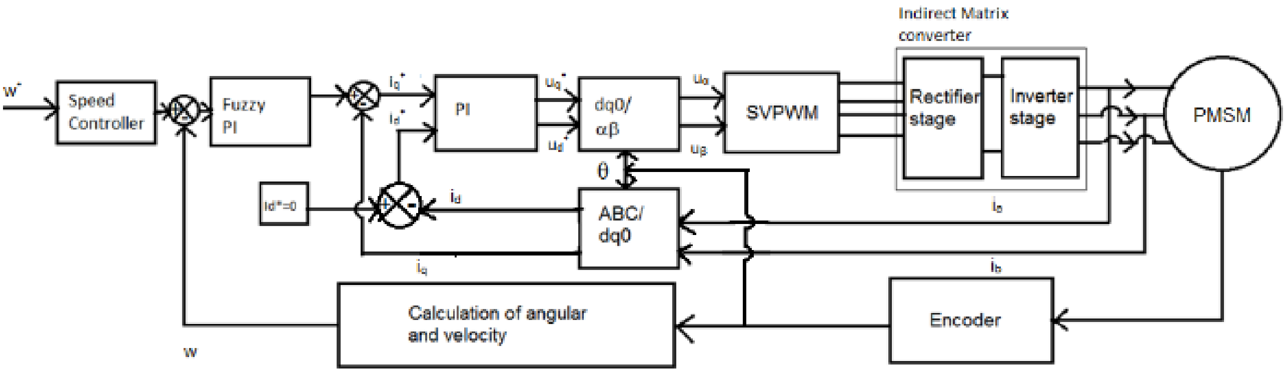

Fig 4. Block diagram of the vector control scheme for a PMSM speed control

$$\begin{pmatrix} i_d^* \\ i_q^* \\ \omega^* \end{pmatrix} = \begin{pmatrix} -\frac{R}{L} & n_p\omega & 0 \\ n_p\omega & -\frac{R}{L} & \frac{n_p K_t}{J} \\ 0 & -\frac{n_p K_t}{L} & -\frac{B}{J} \end{pmatrix} \begin{pmatrix} i_d \\ i_q \\ \omega \end{pmatrix} + \begin{pmatrix} \frac{u_d}{L} \\ \frac{u_q}{L} \\ -\frac{T_L}{J} \end{pmatrix} \quad (1)$$

Where i_d and i_q are the stator current, and u_d and u_q are the stator voltages along the d-axis and q-axis respectively, R is stator resistance, L stator inductance, K_t torque constant, ω is the angular velocity, B is the viscous friction co-efficient, J is the moment of inertia, and T_L load torque.

From fig.4, it is seen that we have followed the $i_d^* = 0$ strategy. Two separate PI controllers are used for both the current loops.

4. Design of internal model control scheme

4.1 Standard Internal Model Control

A standard internal model controller is known for its robustness and stability (C. E. Garcia and M. Morari *Ind. Eng. Chem. Process Des. Develop.*, 1982; Rivals and Z. L. Personna *IEEE Trans. Neural Netw*, 2000). The block diagram describes the control parameters as a sketch. From the figure 5, the generalized PMSM involves the PMSM and the two separate current loops, $G_m(s)$ represents the Internal model and $C_1(s)$ represents the controller.

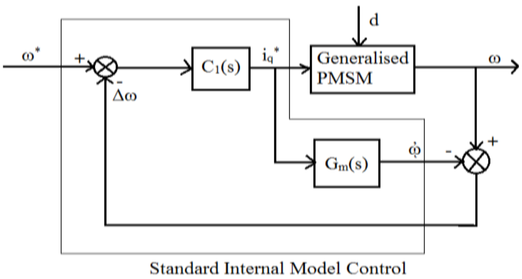

Fig 5. Block diagram of standard internal model control scheme

The equation derived can be represented as,

$$\omega^* = \frac{K_t i_q}{J} - \frac{B\omega}{J} - \frac{T_L}{J} = \frac{K_t i_q^*}{J} - \frac{B\omega}{J} - \frac{K_t d(t)}{J} \quad (2)$$

Where $d(t) = -T_L/K_t - (i_q^* - i_q)$ is the lumped disturbance which represents both the internal disturbance and the tracking error of current loop i_q. The generalized PMSM G_p can be described as follows,

$$G_p(s) = \frac{1}{a_p s + b_p} \quad (3)$$

Where $a_p = J/K_t$ and $b_p = B/K_t$,
and G_d can be represented as

$$G_m(s) = \frac{1}{a_m s + b_m} \quad (4)$$

In an ideal Internal model control, the controller is represented as $C_1(s)=G_p^{-1}(s)$. But when this condition is satisfied $\omega=\omega^*$, which is possible only in the ideal condition. In practical circumstances, there will be error due to unmodeled dynamics, nonlinearity, etc., In order to overcome these errors, we include a filter Q(s).

$$C_1(s) = G_m^{-1} Q_1(s) = G_m^{-1} \frac{1}{\varepsilon s + 1} \quad (5)$$

Where ε is the time constant of the filter.
From fig. 5

$$\Omega(s) = \frac{C_1(s) G_p(s)}{1 + C_1(s)[G_p(s) - G_m(s)]} \Omega^* - \frac{G_p(s)[1 - C_1(s) G_m(s)]}{1 + C_1(s)[G_p(s) - G_m(s)]} D(s) \quad (6)$$

Considering $G_p(s) = G_m(s)$, then from (5) and (6),

$$\Omega(s) = \frac{1}{\varepsilon s + 1} \Omega^* - \frac{\varepsilon s}{(a_p s + b_p)(\varepsilon s + 1)} D(s) \quad (7)$$

It could be seen from equ(7), $G_p(s)$ that is incorporated in the transfer function between Ω(s)and D(s)and influences the heap unsettling influence dismissal execution, regardless of how the parameter of the IMC filter $Q_1(s)$ is tuned. Particularly for a plant with a vast time constant, the recovery trajectory of the load disturbance rejection may have a long tail (T. Liu and F.Gao *Contr. Theory Appl*, 2010; G. Stephanopoulos and H. P. Huang *Chem. Eng. Sci*, 1986) Then again, all control frameworks have some kind of control input saturation in true provisions. Despite the fact that we can make the parameter ε little enough to enhance the load disturbance rejection performance, the yield of internal model controller may surpass the saturation furthest reaches of i_q what's more this will debase the tracking performance to some degree. The reason is that if there is no model mistake and disturbance, the IMC framework will turn into an open loop framework. Because of control input saturation, some wanted control data might lost, which may produce a seriously degrading property that can genuinely corrupt the execution of control framework (Awaya, Y. Kato, I. Miyake, and M. Ito *Proc. Power Electron. Motion Control Conf*, 1992)

4.1.2 Modified Internal model control

In place to upgrade the capabilities of tracking and load disturbance rejection of the framework, a feedback control term $C_2(s)$ is outlined taking into account the standard internal model control structure (P. C. Krause *Analysis of ElectricMachinery*, 1995).

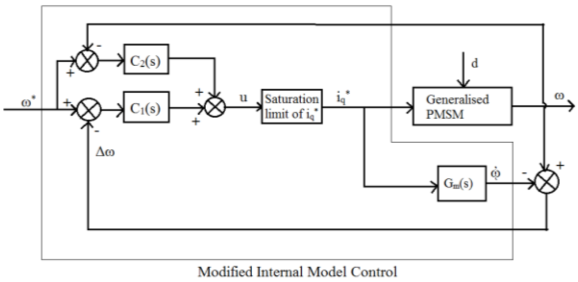

Fig 6. MATLAB simulation of Modified Internal Model Control

Utilizing the two-port IMC structure in, an modified IMC scheme for PMSM is proposed, as demonstrated in Fig. 3. Note that the control input in practice typically is restricted in amplitude. Accordingly the relationship between i_q^* and u is

$$i_q^* = \begin{cases} u, & |u| \le i_{q\,max} \\ i_{q\,max}.\,sign(u), & |u| > i_{q\,max} \end{cases}$$

$C_2(s)$ is designed to be a proportional term,

$$C_2(s) = k_p \tag{8}$$

Ignoring saturation, let i_q^*=u, then from fig 6,

$$\Omega(s) = \frac{[C_1(s)+C_2(s)]G_p(s)}{1+C_1(s)[G_p(s)-G_m(s)]+C_2(s)G_p(s)}\Omega^*(s) - \frac{G_p(s)[1-C_1(s)G_m(s)]}{1+C_1[G_p(s)-G_m(s)]+C_2(s)G_p(s)}D(s) \tag{9}$$

When $G_p(s) = G_m(s)$, from (5), (8) and (9),

$$\Omega(s) = \frac{(k_p\varepsilon+a_p s)s+k_p+b_p}{(a_p s+k_p+b_p)(\varepsilon s+1)}\Omega^*(s) - \frac{\varepsilon s}{(a_p s+k_p+b_p)(\varepsilon s+1)}D(s) \tag{10}$$

For load disturbance rejection performance, contrasted with equ (7)and, it might be seen that the feedback control term kp could be balanced appropriately to decrease the time constant, i.e., $a_p/(b_p+k_p) < a_p/b_p$ which can make the recovery trajectory in the vicinity of load disturbance quick to void a long tail. Besides, when the output of the modified IMC controller is saturated, the yield of the field control term $C_2(s)$ can adjust for the impact of control input saturation as anti-windup remuneration to tracking performance. Through changing the parameter k_p appropriately, the closed circle framework can get a great capacity of tracking and load disturbance rejection.

5. Simulation and experimental results

The parameter used in this experiment are, rated speed n_N=3000rpm, rated torque T_L= 2.4N.m, number pairs n_P=4, stator resistance R= 1.74Ω, stator inductance L= 4mH, moment of inertia J_n=1.78x10^{-4}kg.m^2, torque constant K_t=1.608 Nm/A and viscous coefficient B= 4.45x10^{-4} Nms/rad. Here in the simulation, assuming the internal model is accurate, i.e., a_m=a_p=6.642x10^{-4}, b_m=b_p=2.767 x10^{-4}, the value of ε is varied with each tests, the PI parameters are kept the same with the proportional gain as 50 and the integral gain as 2500. The saturation limit of q-axis reference current is 9.42A or -9.42A.

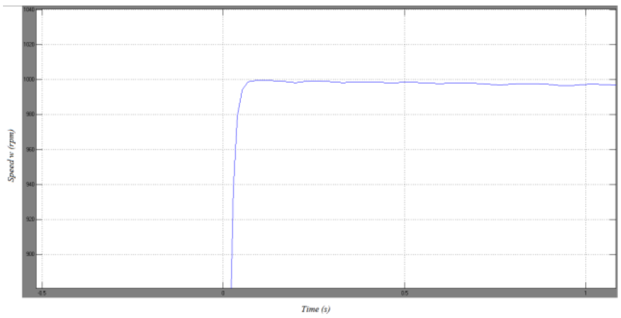

Fig 7. Speed response of PMSM using Standard internal model control for ε= 0.01

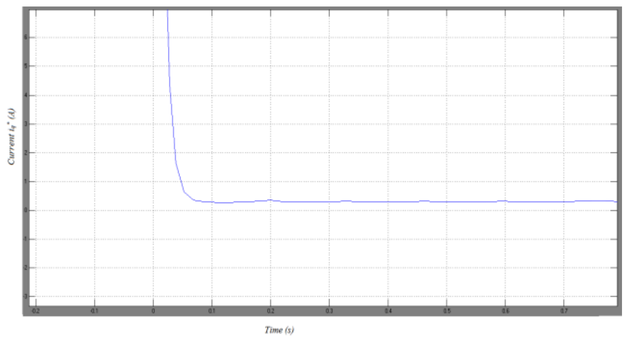

Fig 8. Stator q-axis current response of Standard Internal model control for ε=0.01

The graph in fig. 7 and fig. 8 shows the response curves of speed and i_q^* under ε= 0.01. We can observe from the graph that after the set point has been reached, the input saturation makes the output to be deviate from the desired set point. As discussed before the value of ε can be increased in order to minimize the effect of the input saturation.

The second set of graphs at fig.9 and fig.10 represents the speed and i_q^* response when ε is set at 0.005, the value of the time constant is reduced for the sake of input saturation. Now, it can be observed that the system undergoes fluctuations when the time constant is reduced. From these results we can assume that the standard internal model Controller is sensitive to input saturation. This will lead to poor tracking and disturbance rejection property of the system.

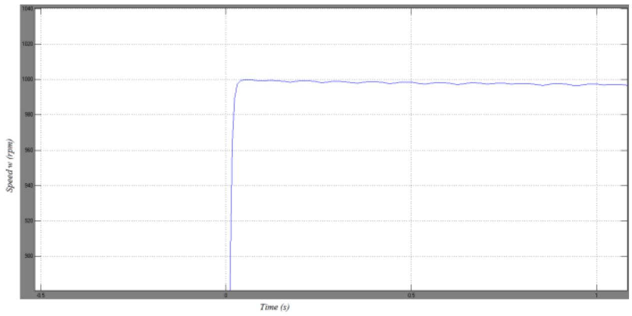

Fig 9. Speed response of PMSM using Standard internal model control for ε= 0.005

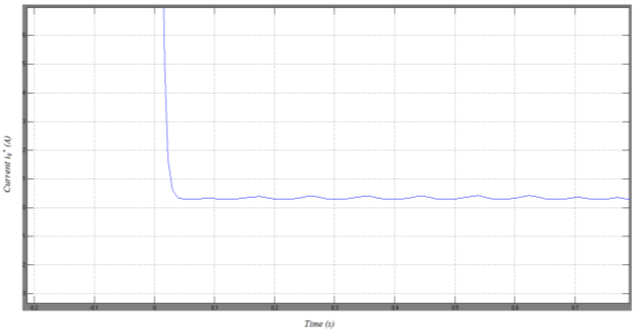

Fig 10. Stator q-axis current of PMSM using standard internal model control=0.005

The modified internal model controller is compared with the standard internal model controller and the results are given in Fig 11, and Fig 12.The parameters used in the modified internal model control scheme is the same as that of the standard internal model controller, a_m=6.642x10^{-4}, b_m=2.767x10^{-4} and ε=0.005, to begin with. The gain of the second filter is calculated as k_p=0.1875. From the graph, we can observe a peak shoot and then the output settles down to the desired set point. The oscillations however are reduced. This shows that the modified internal model control is less sensitive to input saturation.

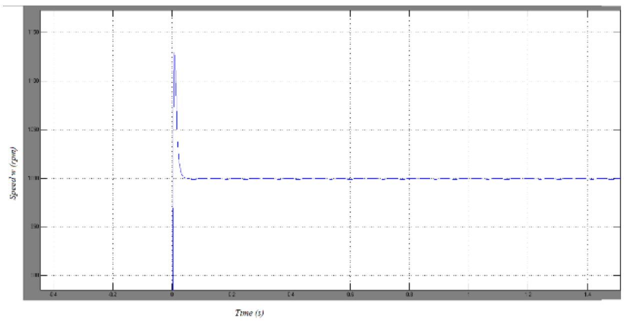

Fig 11. Speed response of PMSM using a Modified Internal Model Control when a_m=6.642x10^{-4} and b_m=2.767x10^{-4}

Comparing the results obtained from the modified internal model control with the standard internal model scheme, the speed curve is very much reduced in the modified scheme, but it was much bigger in the standard scheme. The speed recovery of the modified internal model, is very much reduced compared to the standard internal model.

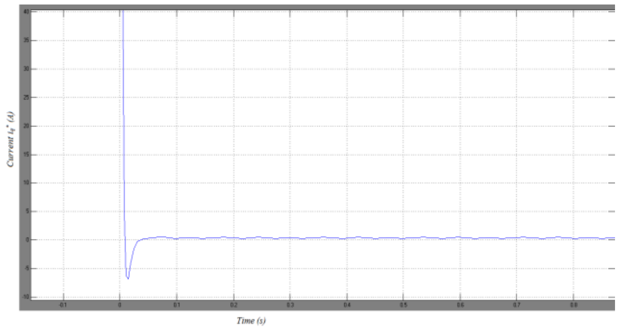

Fig 12. Stator q-axis stator current of a PMSM using Modified internal model control when a_m=6.642x10^{-4} and b_m=2.767x10^{-4}

From these experiments and results it can be concluded that the modified internal model controller has better tracking and disturbance rejection and less sensitive to input saturation compared with the standard internal model controller.

5.1. Adaptive control of PMSM

For the inertia variety case, to guarantee the adjustment capability of closed loop system, it is normal that if the inertia shifts, the internal model furthermore the control parameters dependent upon the internal model might be intelligently changed. Accordingly, a versatile IMC control plan might be created.

The block diagram of adaptive IMC design for PMSM speed regulation system is indicated in Fig 13, shows the subtle element outline of adaptive IMC design. A parameter autotuning system is received to tune the parameter a_m by utilizing the evaluated idleness J_m. The outflow of adaptive internal model controller is as takes after:

Internal model,

$$\hat{G}_m(s) = \frac{1}{\hat{a}_m s + b_m} \tag{11}$$

Internal model controller

$$C_1(s) = \hat{G}_m^{-1}(s) Q_1(s)$$

Once the inertia is identified, a_m can be tuned in accordance with the inertia

5.2. Inertia identification

In this paper, we receive the strategy dependent upon DOB (Disturbance observer) to distinguish inertia. The strategy evaluates the external disturbances and friction in the model by disturbance estimators and afterward acquire an evaluation of inertia (S. M. Yang and Y. J. Deng *Proc. 40th IAS Annu. Meeting*, 2005; J. W. Choi, S. C. Lee, and H. G. Kim *Proc. Inst. Elect. Eng.-Electr. Power Appl.*,

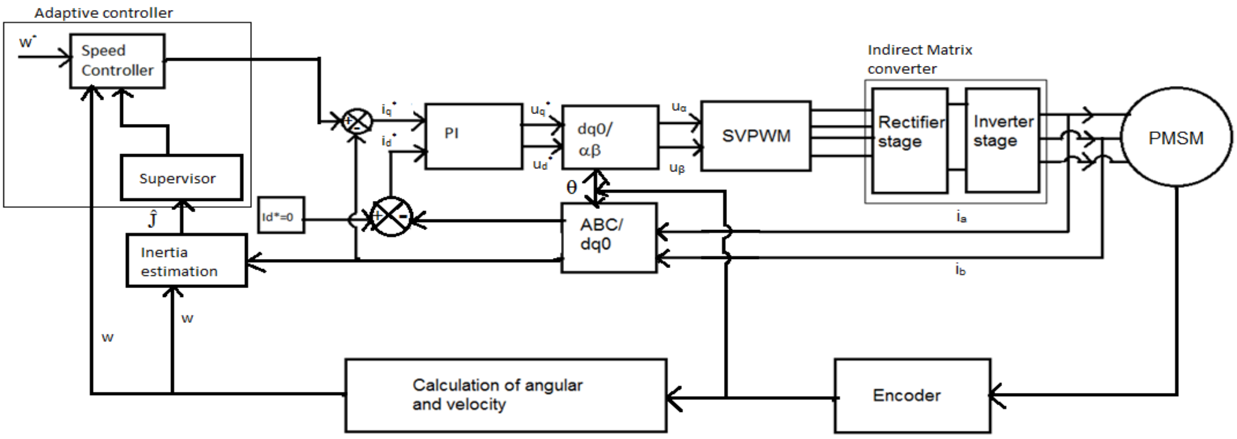

Fig 13. Block Diagram of adaptive PMSM speed control drive

2006; B. Kosko *NN and Fuzzy System: A Dynamical Systems Approach to Machine Intelligence*, 1992). The adequacy of the strategy is checked by exploratory outcomes as in. In this strategy, a test signal for inertia identification is the intermittent pace order that fulfills

$$\omega^*(t+T)=\omega^*(t \qquad (12)$$

where T is the period of speed command.

5.3. Adaptive laws

5.3.1 Linear adaptive law: At the point when inertia shifts, we can tune the parameter $\hat{a}_m$ of the velocity controller by the estimation of inertia. To guarantee the execution of the system, a linear relationship between $\hat{a}_m$ and J is made, e.g., $\hat{a}_m=J/k_t$. We can get the ratio of the real inertia to the original inertia $\delta=\hat{J}/J_n$ by the estimation of inertia. The last parameter might be communicated as follows:

$$\hat{a}_m=\delta\hat{a}_m$$

5.3.2 Fuzzy adaptive laws: $\hat{a}_m$ is hypothetically expected to be linearly tuned with the change of inertia, i.e., $\hat{a}_m=J/K_t$. Nonetheless, in useful provisions, because of the presence of control input saturation, the linear adaptive law may not be the most sufficient result.

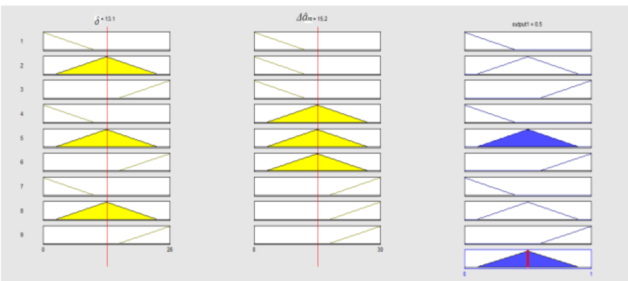

Fig 14. Membership function obtained using triangular membership method. It is a mamdani-type fuzzy inference system.

To get a finer execution of the framework, a practical relationship between am and j ought to be made. Some apriori exploratory tests ought to be carried out to help to choose the tuning representation for the parameter $\hat{a}_m$. So the internal model controller $C_1(s)$ what's more the internal model $G_m(s)$ both are balanced legitimately as stated by the parameter $\hat{a}_m$, which is predictable with internal model design technique. To this end, a fuzzy inference engine (B. Kosko *NN and Fuzzy System: A Dynamical Systems Approach to Machine Intelligence*, 1992; L. Zadeh *IEEE Trans. Syst.. Man, Cyberna*, 1973), is picked to depict the auto tuning function for the parameter $\hat{a}_m$. The fuzzy execute is the one-enter one-output case. By simulation and experimental, we at long last get the accessible assemblies of membership functions and fuzzy rules, as indicated in Fig 14. We can acquire the proportion of the actual inertia to the original inertia $\delta=\hat{J}/J_n$ by the estimation of inertia. The inertia ratio δ is utilized as the input of the fuzzy inference system, while $\Delta\hat{a}_m$ is used as the output of the fuzzy inference system. The last parameter after fuzzy tuning could be expressed as takes after:

$$\hat{a}_m=a_m+\gamma\Delta a_m$$

where γ is the proportional factor.

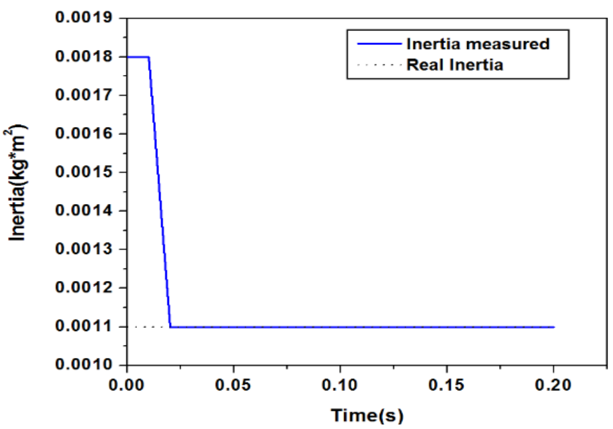

Fig 15. Output graph representing the real inertia and the obtained inertia using the Fuzzy adaptive law control scheme in PMSM

Here, we expect that the reach of the proportion $\delta=\hat{J}/J_n$ of inertia is (0, 25]. At that point, the fuzzy set of δ might be picked as *P1, P2, P3, P4, P5, P6, P7, P8*. The fuzzy set of $\Delta\hat{a}_m$ can likewise be picked as *P1, P2, P3, P4, P5, P6, P7, P8*. The range of the ratio of dam is (0, 20]. The membership functions of the two fuzzy sets are demonstrated in Fig 15. The fuzzy inference standards are as takes after: If δ is P_i, then dam is P_i (i=1,2,3,....8). In this paper, we utilize a Mamdani-type fuzzy inference system and get $\Delta\hat{a}_m$ by utilizing the center of gravity system. The parameter $\hat{a}_m$ is chosen after fuzzy inference

References

Y. X. Su, C. H. Zheng, and B. Y. Duan (2005), Automatic disturbances rejection controller for precise motion control of permanent-magnet synchronous motors, *IEEE Trans. Ind. Electron.*, vol. 52, no. 3, pp. 814–823.

K. H. Kim and M.-J. Youn (2002), A nonlinear speed control for a PM synchronous motor using a simple disturbance estimation technique, *IEEE Trans. Ind. Electron.*, vol. 49, no. 3, pp. 524–535.

C. Baik, K.-H. Kim, and M. J. Youn (2000), Robust nonlinear speed control of PM synchronous motor using boundary layer integral sliding mode control technique, *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 1, pp. 47–54.

S. H. Li and Z. G. Liu (2009), Adaptive speed control for permanent magnet synchronous motor systemwith variations of load inertia, *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3050–3059.

Y. A.-R. I. Mohamed (2007), Design and implementation of a robust current control scheme for a PMSM vector drive with a simple adaptive disturbance observer, *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 1981–1988.

S. M. Yang and Y. J. Deng (2005), Observer-based inertia identification for autotuning servo motor drivers, in *Proc. 40th IAS Annu. Meeting*, pp. 968–972..

C. E. Garcia and M. Morari (1982), Intenal model control-1: A unifying review and some new results, *Ind. Eng. Chem. Process Des. Develop.*, vol. 21, no. 2, pp. 308–323.

M. Morari and E. Zafirious (1989), *Robust Process Control*. Englewood Cliffs, NJ: Prentice-Hall.

Rivals and Z. L. Personna (2000), Nonlinear internal model control using neural networks: Application to process with delay and design issues, *IEEE Trans. Neural Netw.*, vol. 11, no. 1, pp. 80–90.

W. F. Xie and A. B. Rad (2000), Fuzzy adaptive internal model control, *IEEE Trans. Ind. Electron.*, vol. 47, no. 1, pp. 193–202.

Q. Zhang and E. A. Zafiriou (1994), A local form of small gain theorem and analysis of feedback Volterra systems, *IEEE Trans. Autom. Control*, vol. 44, no. 3, pp. 635–640.

G. Horn, J. R. Arulandu, and R. D. Braatz (1996), Improved filter design in internal model control, *Ind. Eng. Chem. Res.*, vol. 35, no. 10, pp. 3437–3441.

T. Liu and F.Gao (2010), New insight into internalmodel control filter design for load disturbance rejection, *Contr. Theory Appl.*, vol. 4, no. 3, pp. 448–460.

G. Stephanopoulos and H. P. Huang (1986), The 2-port control system, *Chem. Eng. Sci.*, vol. 41, no. 6, pp. 1611–1630.

P. C. Krause (1995), *Analysis of ElectricMachinery*, 2nd ed. New York:Mc-Graw-Hill.

C. Eric (1995), Internal model predictive control, *Automatica*, vol. 31, no.10, pp. 1471–1482.

Awaya, Y. Kato, I. Miyake, and M. Ito (1992), New motion control with inertia identification function using disturbance observer, in *Proc. Power Electron. Motion Control Conf*, pp.77–81.

J. W. Choi, S. C. Lee, and H. G. Kim (May 2006), Inertia identification algorithm for high-performance speed control of electric motors, *Proc. Inst. Elect. Eng.-Electr. Power Appl.*, vol. 153, no. 3, pp. 79–386.

B. Kosko (1992), *NN and Fuzzy System: A Dynamical Systems Approach to Machine Intelligence*. Englewood Cliffs, NJ: Prentice-Hall.

L. Zadeh (1973), Outline of a new approach to the analysis of complex systems and decision processes, *IEEE Trans. Syst.. Man, Cybern*, vol. 3, no. 1, pp. 28–44.