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Analysis of Different Speed Control Techniques Using PMSM

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Abstract: This paper present the different speed control techniques using permanent magnet synchronous motor. PMSM is generally used in AC servo drives and industry because application requires good speed controllers with high accuracy, high torque coefficient, and low ripple torque, high power density, high efficiency in the design process and implementation as compare to the other motors used in drives. Many speed control techniques are available and these control techniques differ from the type of controller used for PMSM to the type of software/hardware implementation. The analysis of various control techniques are highlighted in this paper with respect to speed control and implementation.

Keywords: PMSM, Field oriented control, Sensor less control, Neural Network controller, Fuzzy Logic Controller.

I. INTRODUCTION

The Permanent Magnet Synchronous Motors (PMSM) is high-performance electromechanical motion devices factually superseding traditional dc servomotors and fractional horsepower induction machines because of their high performance capability. The performance of PMSM which requires fast transient response must be improved in many applications. High-performance motor control is characterized by trouble free rotation over the entire speed range of the motor, full torque control at zero speed, and fast acceleration and deceleration. In order to optimize the speed-control performance of the PMSM system with different disturbances and uncertainties, different speed control technics have been developed to find out different solutions for the PMSM drive control having the features of high speed and precise torque response.

A "Permanent Magnet Synchronous Motor" (PMSM) or "Permanent-Magnet Motor" (PMM) is a synchronous motor that uses permanent magnets rather than windings in the rotor that generate invariable magnetic field. The PMSM can be thought of as a cross between an AC induction motor and a brushless DC motor (BLDC). They have rotor construction similar to BLDC motors which contain permanent magnets. However, their stator construction resembles that of its ACIM cousin, where the windings are constructed in such a way as to build a sinusoidal flux density in the airgap of the machine. As a result, they perform best when driven by sinusoidal waveforms. There are two types of PMSM be dependent on the mounting of permanent magnets. One is surface mounted PMSM and another is Interior Permanent Magnet. Interior Permanent Magnet (IPM) is the most widely used type in PMSM. PMSM are typically used for high-efficiency and high-performance motor drives. Because of their high performance/cost ratio, PMSM has chosen in variable speed application is greater.

Recent research has reported that the PMSM is being increasingly used in high torque per current ratio and high-performance applications, such as robots and industrial machines, which require speed controllers that not only handle with accuracy and high performance, but also flexibility and efficiency in the design process and implementation. The conventional PI and proportional integral derivative (PID) controllers have been widely used as speed controllers in PMSM drives. However, in a practical PMSM is a nonlinear system there are large number of the disturbances and uncertainties as well as parameters variations [1, 2, 3] which may come internally or externally like un modeled dynamics, parameter variation, friction force and load disturbances.

Therefore, a suitable control technique is necessary in order to obtain good adjustment performances in various working conditions. But, it is very difficult to distinguish system characteristics and dynamic control parameters in real time due to the complexity of PMSM servo system. Therefore, many nonlinear control methods of PMSM has been developed to improve the system control performances for various disturbances and uncertainties, thus various methods of nonlinear control methods have been developed for PMSM system, such as adaptive control [4, 5], robust control [6], sliding mode control [7], input-output linearization control [2], back stepping control [8], neural network control [5], fuzzy control [9] and finite-time control [10], predictive control [15], intelligent control [9, 10], etc.

All these control methods have been designed to improve the performance of PMSM at different load condition and various speeds. This paper presents the FOC, sensor less control, Neural Network controller and FL speed controllers for the PMSM system. These controllers are chosen to reach zero steady state error, minimum

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overshoot and fast settling time. Similarly, these methods can guarantee both closed-loop stability and robust control of the PMSM drive systems over the existing control methods. A simulation system was implemented in the MATLAB environment to verify the system results. Under the load changes and parameter variations of the PMSM drive system the dynamic performance of the system was studied.

II. MODELLING OF PMSM

The demand for variable speed drives in both low and high power applications has resulted in a developing the different control strategy plays a important role in fulfilling the demands of each application to improve the performance of PMSM at the various speeds and load conditions. In order to apply various speed control system of PMSM, however, the original non-linear, mathematical model must first be linearized.

Mathematical model of the PMSM system can be expressed by such equations in the rotating reference frame (d-q reference frame). At any time t, the rotating rotor d-axis makes an angle θr with the fixed stator phase axis and rotating stator MMF makes an angle δ' with the rotor d-axis.The model of PMSM without damper windinghas been developed on rotor reference frame using the following assumptions:

- Saturation is neglected.
- Windings are distributed sinusoidal
- The induced EMF is sinusoidal.
- Eddy currents and hysteresis losses arenegligible.

There are no field current dynamics in PMSM.The electrical and mechanical equations ofPMSM in rotor (d-q) frame is

$$V^r_{ds} = i^r_{ds} R_d + \frac{d}{dt}\psi^r_{ds} - \omega_r \psi^r_{qs} \quad (1)$$

$$V^r_{qs} = i^r_{qs} R_q + \frac{d}{dt}\psi^r_{qs} + \omega_r \psi^r_{ds}$$

(2)

$$\psi^r_{ds} = L_{ds} i^r_{ds} + \psi_{fr}$$

(3)

$$\psi^r_{qs} = L_{qs} i^r_{qs}$$

(4)

$$\psi_{fr} = L_{md} + i_{fr}$$

(5)

Where,

V^r_{ds}, V^r_{qs} are dq axis stator voltages

ψ^r_{ds}, ψ^r_{qs} are flux linkage in dq axis stator

ψ_{fr} is the field flux

i^r_{ds}, i^r_{qs} are dq axis stator currents

L_{ds}, L_{qs} are dq axis stator inductances

L_{md} is d axis rotor inductance

i_{fr} is field current.

In matrix form,

$$\begin{bmatrix} V^r_{ds} \\ V^r_{qs} \end{bmatrix} = \begin{bmatrix} R_d + L_{ds}\frac{d}{dt} & -\omega_r L_{qs} \\ \omega_r L_{ds} & R_q + L_{qs}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i^r_{ds} \\ i^r_{qs} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r \psi_{fr} \end{bmatrix} \quad (6)$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\psi^r_{ds} i^r_{qs} - \psi^r_{qs} i^r_{ds}\right)$$

(7)

The torque equation for PMSM resembles to that of the regular DC motor. Therefore, it may facilitate the control of the machine very efficiently. The motor currents are decomposed into id and iq components in the rotor based dq coordinates system. The maximum torque is obtained with id=0 which corresponds to the case when the rotor and stator fluxes are perpendicular. The operation of the drive is then similar to that of armature current controlled DC motor.

III. CONTROL STRATEGIES AND METHODOLOGIES

The various control techniques are designed to control speed, torque, position of rotor to achieve high performance & high efficiency control. This review has spotlight a broad classification of speed control techniques. The vector control technique is one of the basic control method used for speed control of PM synchronous motors. The vector control technique is also referred as field-oriented control (FOC). In particular, the method implies the measurement of motor currents and successively their transformation into a coordinate system rotating with the rotor of the machine. Sensor less Control is also one of the methods for speed control. Usually the rotor position information is needed to efficiently control the performance of the PMSM, but a rotor position sensor on the shaft decreases the robustness and reliability of the entire system in some applications. Therefore, the aim is not to use this mechanical sensor to measure the rotor position directly but some indirect techniques are available to estimate the rotor position. Field or Flux Weakening Control method is also one of the methods used to overcome the base speed limitation. Moreover Model Predictive Control (MPC) is one of the most practical advanced control techniques in industrial applications. In addition techniques developed from artificial intelligence such as Fuzzy Logic Control, Neural Networks, Neuro-Fuzzy Hybrid Systems, are used for speed control of PMSM. Other controlling methods such as MRAS or hybrid methods such as combination of fuzzy logic and sensor less or fuzzy-neuro also can be used.

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Depending on the control strategies & methodologies for hardware implementation, the speed control techniques can be widely classified into intelligent control techniques (such as fuzzy logic control, neural networks), sensor less speed control method, hybrid techniques and the other techniques/ methods. A review on such different control strategies is highlighted in this study with respect to speed control & implementation of a speed controller.

A. Field Oriented Control

Field Oriented Control is the technique used to independently decoupled control of torque and flux by transforming the stator current quantities (phase currents) from stationary reference frame to torque and flux producing currents components in rotating reference frame just like dc machine. It improves both transient and steady state response of PMSM

$$T_e = \frac{3}{2}\frac{P}{2}\left(\frac{1}{2}\left(L_{ds} - L_{qs}\right)i_s^{2}\sin 2\delta' + L_{md}\, i_{fr}^{r}\, i_s \sin\delta'\right)$$

(6)

For field oriented control selecting the $\delta' = \frac{\pi}{2}$ so we get the torque expression like,

$$T_e = \frac{3}{2}\frac{P}{2}\left(L_{md}\, i_{fr}^{r}\, i_s\right)$$

(7)

$$\bar{i}_S = \bar{i}_T + \bar{i}_F$$

(8)

Stator current has a two component,

$\bar{i}_T$ is stator torque component of current

$\bar{i}_F$ is stator flux component of current

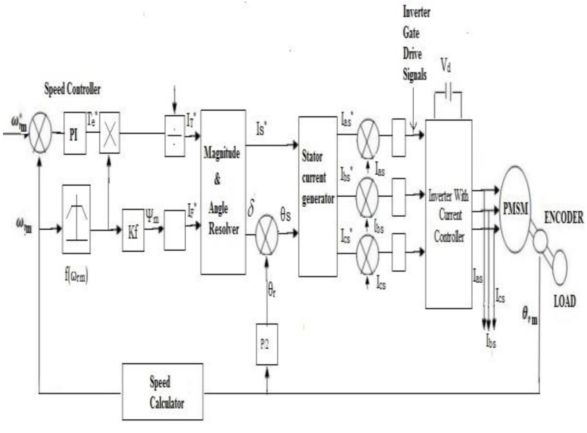

Fig. 1. Block Diagram of Vector control speed control of PMSM

Fig. 1 shows the vector controlled speed control of PMSM drive. The reference speed is compared with actual speed. PI controller will be giving the magnitude of torque which is controlled as per the speed. Up to the base speed torque will be constant. After the base speed torque will be reduced for the field weakening region. So this is multiplied with the factor that is coming from the field weakening performance to obtain the reference torque Te^*. This Te^* is divided by a constant to give as a torque component of current I_T.

Similarly the flux component is obtain by a functiongenerator f (ω_{rm}) and this multiplied by constant Kf to give the magnetizing flux (Ψ_m). This magnetizing flux used in a function block to give an I_F (Flux component of current). Thus the I_T & I_F are transform to the production of reference stator current.Magnitude and angle resolver used to Convert I_T & I_F into polar components as amplitude I_S and phase angle (delta prime).This delta prime is added with rotor angle θr and produce θs.

The current Is^* and θs are given to the input of stator current generator to produce the stator current reference I_{as}^*, I_{bs}^*, I_{cs}^*.

These currents have to in place of the machine. So the inverter this is operated with the current controller.The actual currents are obtained by hall sensor in the motor and compared with the reference current will be giving the error. This error is given to the hysteresis controller to control the inverter.All the Synchronous machine requires a position feedback for the closed loop control. So the encoder in the rotor mounted on the rotor shaft which will measure the position, and this position will be used for control of the inverter.So the position sensor (rotor position encoder) to obtain the mechanical position θ_{rm} that is multiplied by pole pair for actualrotor position in electrical angle θ_r. This position is persist through another computational block (speed calculator) to find out the mechanical speed ω_{rm}. This ω_{rm} taken as a feedback and compare with the reference speed. The PI controller used here as a speed controller.The block diagram can control the speed, below the base speed and above the base speed. Below the base speed the magnetizing flux will be constant. Ψm is the magnetizing the flux. Which is the resultant of field and stator.

Advantages of FOC

- Transformation of a complex and coupled AC model into a simple linear system
- Independent control of torque and flux, similar to a DC motor
- Fast dynamic response and good transient and steady state performance
- High torque and low current at start up
- High Efficiency
- Wide speed range through field weakening

B. Sensorless Control

Process of permanent magnet synchronous motor drive needs position sensors in the rotor shaft when operated without damper winding. The necessity of knowing the

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rotor position demand the development of devices for position measurement. It is necessary of the accurate estimation of rotor position because, if estimated inaccurately, then the motor starting torque reduced, and the motor may temporarily rotate in the wrong direction [11]. There are some devices available for the measurement of position, optical encoder, resolvers, potentiometer and linear variable differential transformer. Among them,encoders and revolvers are most commonly used in motors to measure the position.

Various techniques to sensorless PMSM drive operation have been reported as sensors produce several disadvantages [12] such as reduced reliability, high cost, size, weight and increased difficulty of the drive system. In many industrial installations, the presence of this shaft sensor may considerably reduce the overall ruggedness of the drive. In others, it may add significantly to the drive cost [13]. The methods to determine the position of the rotor in electric machines by measuring only their voltages and currents, significantly in recent years [14]. These methods are usually designated as sensorless, encoderless, or self-sensing [15], [16]. The PMSM torque control requires knowledge of the rotor position to perform an effective MMF control which is control by stator current control [17]. In addition, for speed control, the speed signal is also required. Motor drives without a position sensor or speed sensor have received much research attention in recent years, for induction motor, BLDC and PMSM motor.

In a PMSM, the rotor position can be determined by the back Electro-Motive Force (EMF) or by the position leaning on of the inductances, flux linkage sensing etc., amongdifferent sensorless control techniques which have been carry out for PMSMs, the very popular method model-based adaptive observers are used. The observer-based estimation has number of advantages over the others because it does not consider steady-state conditions, and stability of the evaluation can be analyzed via rigorous control theory [18]. Fig. 2 shows a schematic of a sensorless scheme.

The Extended Kalman Filter (EKF) is an optimal estimator in the least-square sense for estimating the states of dynamic non-linear systems, and it is thus a viable and computationally efficient candidate for the on-line determination of rotor position and speed of a PMSM. Theoretical basis and digital implementation of EKF have been deeply investigated [19]. A

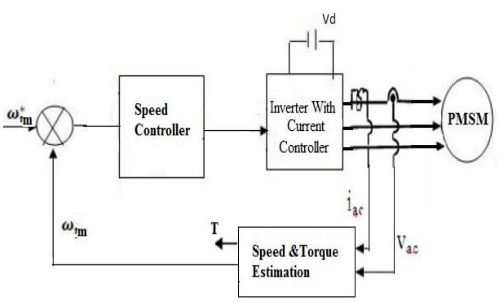

Fig. 2. Sensorless operation of PMSM motor drive

novel method i.e. adjustable DC bus voltage, has been proposed in 2009 [19] for low speed EKF sensorless control of permanent magnet synchronous motor (PMSM) drives. This assumes that the measurement noise and disturbance noise are not correlated. The noise sources take account of measurement and modeling inaccuracies. In the very first stage at the time of calculations, the states are predicted by using a mathematical model and in the second stage; the predicted states are continuously corrected by using afeedback correction scheme. This scheme uses actual measured states by summing a term to the predicted states which is obtained in the very first stage.

The additional term contains the weighted difference of the measured and calculated output signals. Based on the deviation obtained from the estimated value, the Extended Kalman Filter (EKF) gives an optimum output value at the next input instant. The EKF estimation is very sensitive to the PM flux linkage error. However, at least one major drawback of the EKF application to sensorless drives whichis not yet solved, is the poor performance in low speed (<5Hz). In addition to the influence of estimation algorithm, the accuracy of system error estimation is mainly determined by the system observability. The observations of EKF filter are voltage and current.

There is not any impact on current data in low speed. But there is one problem that is the harmonic component has a high ratio in voltage data. This estimation fluctuates severely because of the slowly changed system error information disturbed by quickly changed random error. That is why the higher ratio of signal-to-noise (SNR) of voltage, there would be a better performance in low speed. A simple method for high Signal-to-noise ratio is to reduce the voltage level of DC bus.

C. Neural Network Control

The application of neural network speed control of PMSM motors has become one of the challenging function in the control system area. The generalized block diagram of the speed control of PMSM motor shown in fig.3

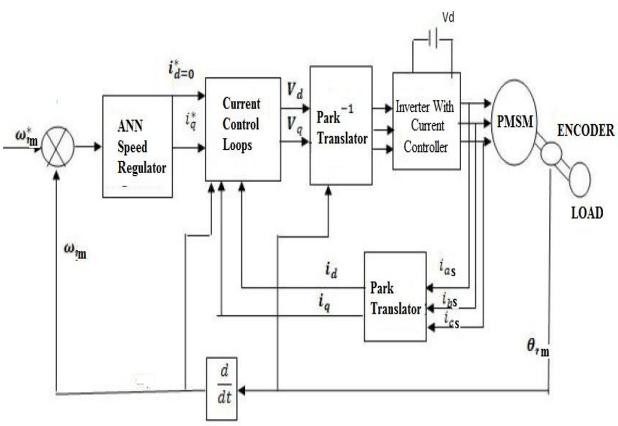

Fig. 3. Speed control of PMSM drive by using ANN Controller

Neural Network is used in the place of PI or PID controller in the conventional system. Comparing the desired set values of torque and speed with actual values togenerate the error signal which is used to compensate the error. Which has been applied to Neural Network to estimate torque, flux or flux angle of the motor at any instant of time. The ANN controller generated the control signals for the firing of power electronics devices, which can be a thyristor, power transistor, IGBT or any other suitable devices.

The application of two types of Artificial-intelligence-based estimators is briefly discussed here; such as artificial neural network (ANN) or a fuzzy-neural network. It is possible to train a supervised multi-layer feed forward ANN with back-propagation training for the estimation of the rotor position and the rotor angle. By using the back-propagation algorithm, the square of the error between the required and actual ANN output is minimized. The trained ANN can then be used in real-time applications. Such an ANN contains an input layer, an output layer and the hidden layers. However, the number of hidden layers to be used is not known in advance; this has to be determined by trial and error, although it should be noted as a guideline that in electrical engineering applications the number of hidden layers is usually one or two. Furthermore, the number of hidden nodes in the hidden layers is also not known in advance and again this has to be obtained by trial and error.

The number of input nodes depends on the type of PMSM (machine with surface-mounted magnets or machine with interior magnets). It is possible to construct such a neural network which also uses at its inputs the stator currents of the machine but for each of the stator currents used, there are two inputs, corresponding to a present and also to a past input. It is an advantage of such an approach that, in contrast to other conventional techniques, it does not require a mathematical model of the machine. In ANN-based approach it is difficult to relate the structure of the network to the physical process and there are no guidelines for the selection of the number of hidden layers and nodes. It is possible to overcome some of the difficulties of the ANN-based approach by using a fuzzy-neural estimator. A fuzzy neural system combines the advantages of fuzzy-logic and neural networks. Number of layers and also the number of nodes are known is the main advantage of a fuzzy-neural network [20].

D. Fuzzy Logic Control

Fuzzy Logic Controllers are more robust to system plant parameter changes than classical PI or PID controllers and have better noise rejection capabilities. The fuzzy adaptive strategies are closer to the experts, reflecting their knowledge and experience. As the modern smooth control strategies grow in complexity, the fuzzy controllers are very competitive in high performance drive applications. As a result, the system performance/complexity ratio is generally higher for adaptive fuzzy controllers [22]. Because it does not require knowledge of the plant's mathematical model and providing the advantages of robust performance for both linear and nonlinear plant functions. A form of knowledge representation suitable for notions that cannot be defined accurately, but which depend upon their contexts. Fuzzy logic is a set of well-defined logic that is available in the membership function to perform some specific electrical task on the electrical problem.For the speed control of PMSM, many controllers are used. In conventional P, PI and PID controllers, which cannot cope up with system's parameter variations because of the required fine tuning is low. Also the performance of such controllers is affected due to the changes in physical parameters like temperature, noise, saturation etc.

Many control system uses adaptive controllers for PMSM drive applications, which can track only linear systems. Hence, fuzzy logic based controller may be used to achieve an effective accurate and faster solutions and to handle complex non-linear characteristics. Fig. 4 shows the block diagram of the fuzzy control system consists respectively of fuzzification, rule data base, rules inference and Defuzzification [27]. A simple structure Fuzzy Logic Controller (FLC) is used in the speed control loop to regulate the motor speed.

The fuzzy PI controller was implemented according to Fig. 3. There are seven triangle memberships representing the Error (e) and Change of Error (Δe) inputs. The normalizing of these membership functions is shown in Fig. 6, where, real range of Error (e) and Change of Error (De) are converted to the inputs of FLC.

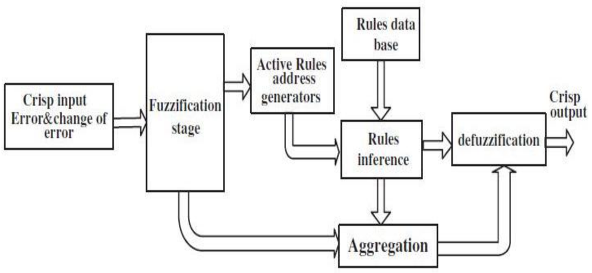

Fig. 4. FLC Architecture

Several fuzzy control applications including the physical systems, require a real time operation to interface high speed constraints [6, 7]. Higher density programmable logic devices, such as field programmable gate array (FPGA) can be used to integrate large amounts of fuzzy logic in a single integratedcircuit (IC).

A direct adaptive controller uses a fuzzy logic system (FLS) as a controller and it incorporates linguistic fuzzy control rulesdirectly into the controller [25]. In this section, we have used a direct adaptive fuzzy control scheme that consists of a fuzzylogic control (FLC), a reference model and an adjusting mechanism as shown in Fig. 5. The detailed description is as follows:

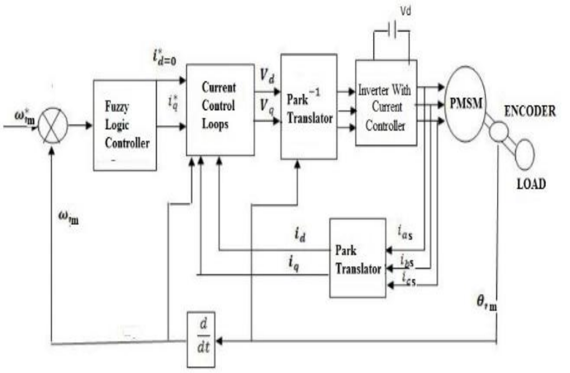

Fig. 5. Block diagram of AFLC

It is the main part of the controller in combination, and this part composed by some sections as follows Fuzzification, Active Rules Address Generator, Rule Inference and Center of Gravity Defuzzification. The tracking Error (e) and Change of Error (Δe) are defined by Eqs. (9) and (10) respectively as follows:

$$e(k) = \omega_{ref} - \omega_{act} \quad (9)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (10)$$

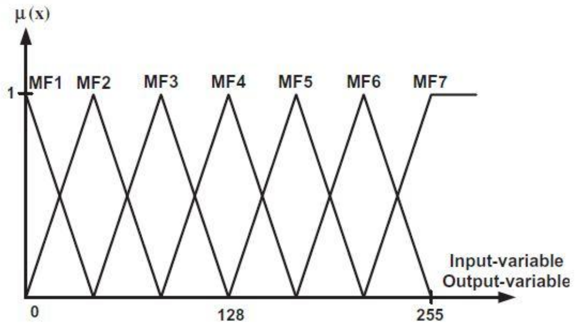

Fig. 6. Input and output membership function

Instead of knowledge about the plant (PMSM motor) to design a FLC some knowledge about adequate plant control actions is used to design an initial control solution. The normalizingof these membership functions is shown in Fig. 6The controlknowledge can be provided for example by human knowledge, and is assumed to be expressed as a set of ''m'' fuzzy IF-THEN rules of the form:

IF e is A_i and Δe is B_i THEN U_f is Z_i (11)

Where, i= 1, 2, 3. . . m. There are seven fuzzy sets for each linguist value {Ai, Bi, Z_i} and 49 fuzzy control rules are designed for two inputs and one output fuzzy system U_f. Amaximum of four rules will be active at any time [26].

$$\mu_z(U_f) = \max_{(j=i,i+1)} \min(\min(\mu_{A_j}(e), \mu_{B_j}(\Delta e)), \mu_{Z_j}(U_f)) \quad (12)$$

$$\mu_z(U_i) = (\mu_{A_j}(e), \mu_{B_j}(\Delta e)) \quad (13)$$

After that, defuzzifier converts Eq. (11) into the following expression:

$$U_f = \frac{\sum_{i=1}^{n} \mu(U_i) \cdot C_i}{\sum_{i=1}^{n} \mu(U_i)} \quad (14)$$

Where, $\mu(U_i)$ is the values of membership function (MF) for output and C_i is the values of output MFs centers. Next this result is transferred to the PMSM motor.

IV. CONCLUSION

The aim of this paper is to present the study of different types control techniques used for speed control of permanent magnet synchronous motor (PMSM). As PMSM is increasingly used in high-performance applications in servo drives and industry, such applications needs speed controllers with high accuracy, high performance and flexibility and efficiency. The study reviews that various approaches are available regarding both the controller type (ranging from fuzzy logic, neural networks to classical PID control algorithms) However, the majority of the reviewed papers lack a holistic modeling of the control system. There is a gap between the design and simulation of the controller and on other side, the design of the hardware implementation. This effect on the accuracy, performance and efficiency of the control system of PMSM. Thus the future scope is to try to fill in the gap in the existing literature by developing a novel system which will overcome drawbacks of the existing methods.

REFERENCES

[1]. K. H. Kim and M. J. Youn, A nonlinear speed control for a PMSM using a simple disturbance estimation technique, IEEE Trans. on Industrial Electronics, vol.49, no.3, pp.524-535, 2002.

[2]. B. Grcar, P. Cafuta, M. Znidaric and F. Gausch, Nonlinear control of synchronous servo drive, IEEE Trans. on Control Systems and Technology, vol.4, no.2, pp.177-184, 1996.

[3]. G. J. Wang, C. T. Fong and K. J. Chang, Neural-network-based self-tuning PI controller for precise motion control of PMAC motors, IEEE Trans. on Industrial Electronics, vol.48, no.2, pp.408-415, 2001.

[4]. S. H. Li and Z. G. Liu, Adaptive speed control for permanent magnet synchronous motor system with variations of load inertia, IEEE Trans. on Industrial Electronics, vol.56, no.8, pp.3050-3059, 2009.

[5]. H. C. Cho, K. S. Lee and M. S. Fadali, Adaptive control of PMSM systems with chaotic nature using Lyapunov stability based feedback linearization, International Journal of Innovative Computing, Information and Control, vol.5, no.2, pp.479-488, 2009.

[6]. T. L. Hsien, Y. Y. Sun and M. C. Tai, H1 control for a sensorless permanent-magnet synchronous drive, IEE Proc. of Electric Power Applications, vol.144, no.3, pp.173-181, 1997.

[7]. R. J. Wai, Total sliding-mode controller for PM synchronous servo motor drive using recurrent fuzzy neural network, IEEE Trans. on Industrial Electronics, vol.8, no.5, pp.926-944, 2001.

[8]. M. Vilathgamuwa, M. A. Rahman, K. Tseng and M. N. Uddin, Nonlinear control of interior permanent magnet synchronous motor, IEEE Trans. on Industry Applications, vol.39, no.2, pp.408-415, 2003.

[9]. Y. S. Kung and M. H. Tsai, FPGA-based speed control IC for PMSM drive with adaptive fuzzy control, IEEE Trans. on Power Electronics, vol.22, no.6, pp.2476-2486, 2007.

[10]. S. H. Li, H. X. Liu and S. H. Ding, A speed control for a PMSM using finite-time feedback control and disturbance compensation, Trans. on the Institute of Measurement and Control, vol.32, no.2, pp.170-187, 2010.
[11]. Y. He, W. Hu, Y. W. J. Wu and Z. Wang and Z.Wanf, "Speed and Position Sensorless Control for Dual-Three-Phase PMSM Drives," IEEE, pp. 945-950, 2009.
[12]. H. Madadi Kojabadi, and M. Ghribi, "MRAS-based Adaptive Speed Estimator in PMSM Drives," IEEE, pp. 569–572, 2006.
[13]. P. P. Acarnley and J. F. Watson, "Review of position-sensorless operation of brushless permanent-magnet machines," IEEE Trans. Ind. Electron. vol. 53, no. 2, pp. 352–362, Apr. 2006.
[14]. Boldea, "Control issues in adjustable speed drives," IEEE Ind. Electron. Mag., vol. 2, no. 3, pp. 32–50, Sep. 2008.
[15]. R. Leidhold, "Position sensorless control of PM Synchronous Motors Based on Zero-Sequence Carrier Injection," IEEE Trans. Ind. Electron., vol. 58, no. 12, pp. 5371–5379, Dec. 2011.
[16]. J.W. Finch and D. Giaouris, "Controlled ac electrical drives," IEEE Trans. Ind. Electron., vol. 55, no. 2, pp. 481–491, Feb. 2008.
[17]. P. Sergeant, F. D. Belie and J. Melkebeek, "Rotor Geometry Design of Interior PMSMs With and Without Flux Barriers for More Accurate Sensorless Control," IEEE Trans. Ind. Electron., vol. 59, no. 6, pp. 2457–2465, June 2012.
[18]. S. Po-ngam, and S. Sangwongwanich, "Stability and Dynamic Performance Improvement of Adaptive Full-Order Observers for Sensorless PMSM Drive," IEEE Trans. Power Electron. vol. 27, no. 2, pp. 588–600, Feb. 2012.
[19]. G. Shan-Mao, H. Feng-You and Z. Hui, "Study on Extend Kalman Filter at low speed in Sensorless PMSM Drives," IEEE International Conf. on Electronic Computer Technology, pp. 311-316, 2009.
[20]. Peter Vas, Sensorless Vector and Direct Torque Control. London: Oxford Univ. Press, 1998.
[21]. Nagib G, Gharieb W, Binder Z. Application of fuzzy control to a non-linear thermal process. In: The 31st conference of the IEEE on decision and control, Tucson, Arizona, December 1992.
[22]. Kumar V, Rana KPS, Kumar V. Real time comparative study of the performance of FPGA based PID and fuzzy controllers for a rectilinear plant. In: IEEE conference publications, power electronics (IICPE), 2010 India international conference, 28–30, January 2011.
[23]. Sakthivel G, Anandhi TS, Natarajan SP. Design of optimized fuzzy logic controller for area minimisation and its FPGA implementation. (IJCSNS) Int J Comput Sci Network Secur 2010;10(8):187–92.
[24]. Precup RE, Hellendoorn H. A survey on industrial applications of fuzzy control'', computers in industry, vol. 62. Elsevier; 2011, p.213–226.
[25]. Kuo B. Automatic control systems. Englewood Cliffs, NJ:Prentice-Hall; 1995.
[26]. Ogata K. Modern control engineering. 3rd ed. Upper Saddle River, NJ: Prentice-Hall; 1997.
[27]. Passino KM, Yurkovich S. Fuzzy control. Addison Wesley Longman, Inc.; 1998, ISBN 0-201-18074-X