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Speed Control of PM Synchronous Motor Drives Using PID and Fuzzy Approach

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Abstract: *This paper proposes an adaptive proportional integral-derivative (PID) speed control scheme for permanent magnet synchronous motor (PMSM) drives. The proposed controller consists of three control terms: a decoupling term, a PID term, and a supervisory term. The first control term is employed to compensate for the nonlinear factors, the second term is made to automatically adjust the control gains, and the third one is designed to guarantee the system stability. Different from the offline-tuning PID controllers, the proposed adaptive controller includes adaptive tuning laws to online adjust the control gains based on the gradient descent method. Thus, it can adaptively deal with any system parameter uncertainties in reality. The proposed scheme is not only simple and easy to implement, but also it guarantees an accurate and fast speed tracking. It is proven that the control system is asymptotically stable. To confirm the effectiveness of the proposed algorithm, the comparative experiments between the proposed adaptive PID controller and the conventional PID controller are performed on the PMSM drive. Finally, it is validated that the proposed design scheme accomplishes the superior control performance (faster transient response and smaller steady-state error) compared to the conventional PID method in the presence of parameter uncertainties.*

Index Terms*: Adaptive control, parameter uncertainties, proportional-integral-derivative (PID) control, surface-mounted permanent magnet synchronous motor (SPMSM)*

I. INTRODUCTION

Since the last three decades AC machine drives are becoming more popular, especially Induction Motor (IM) and Permanent Magnet Synchronous Motor, but with some special characteristics, the PMSM drives are ready to meet up sophisticated needs such as fast dynamic response, high power factor, and wide operating speed range, as a result, a gradual gain in the use of PMSM drives will surely be witness in the future in low and mid power applications.

In a PMSM, the dc field winding of the rotor is replaced by a permanent magnet to produce the air-gap magnetic flux. Having the magnets on the rotor, electrical losses due to field winding of the machine get reduced and the lack of the field losses improves the thermal characteristics of the PM machines and its efficiency. Absence of mechanical components like brushes and slip rings makes the motor lighter, high power to weight ratio for which a higher efficiency and reliability is achieved.

Because of the advantages, permanent magnet synchronous generator is preferred in wind turbine applications. Disadvantages of PM machines are: at high temperature, demagnetization of the magnet, manufacturing difficulties and high cost of PM material.

II. ELECTRICAL MOTORS

Electrical motor is an electromechanical energy converter that translates its input electrical energy into output mechanical energy. They are available for more than a century and are playing a very vital role in the development of modern technology. Better understanding of the energy conversion principles coupled with the evolution of new and improved materials have contributed to advanced machine design. The theory of finite element analysis which is introduced recently has helped in further development and design optimization of electrical motors. The advent of modern digital processors and massive development of power electronics and semiconductor devices have made revolutionary contribution in the control and application of these devices. The direct current (dc) motor, induction motor and synchronous motor are the most commonly used in industrial applications. As a result of tremendous research and advancements InTechnology, special machines such as brushless dc motor (BLDC), switched reluctance motor (SRM), permanent magnet synchronous motor (PMSM) and permanent magnet hysteresis motor are being successfully developed and used for industrial and commercial applications (Bose 2011).The dc motor was dominating the field of variable speed dives until 1980.

They are still used in industries for the advantages in terms of control. The drive configuration is simple with a converter. Torque control in dc motor is very fast because of the inherent decoupling of field flux and armature magneto motive force (MMF). Below the rated speed, the dc armature voltage is controlled at constant field flux to control the torque for speed regulation. Above the rated speed, the field current is weakened at the rated armature current in order to control the speed at reduce torque. However, there are some limitations associated with dc motors such as low efficiency, high inertia, and narrow range of speed variations, low load capability, inherently fast torque response and problems associated with commutators and brushes. They require periodic maintenance, which makes them less reliable (Bose 1994).In the recent years dc motors have become obsolete and alternating current (ac) motors are invariably preferred.

Before the advent of power semiconductor devices, they are commonly accepted for fixed speed operation. However, the advancements in power semiconductor devices and processor technology have expanded the use of them for variable speed applications in industries (Bose 1988). Among the ac motors, the induction motor, particularly the cage type, are by far most commonly used in constant and variable speed drives.

They are simple in construction, economical, rugged, and reliable and are available in a wide power range, including fractional kilowatt (kW) to multi-mega watt capacities. A substantial amount of utility energy is consumed by them. The dynamic control of induction motor drive depends on the exact modeling and estimation of motor parameters in addition to the complicated control circuits. But due to the technological advancements in control, signal estimation, digital signal processing (DSP)and application specific integrated circuits (ASIC), these drives are made economical and superior in performance, and their applications are fast increasing (Bose 2009).3A considerable amount of interest is developed on synchronous motor for variable speed drive in the recent years.

Since the field of the synchronous motor is excited separately by dc source, they can operate at lagging, leading and unity power factor. Operating them near unity power factor not only reduces the armature copper loss but also the size of inverter with simple commutation and control circuits. The conventional wound field

Synchronous motor (WFSM) is large in size (Bose 1994). The dc excitation for the rotor can be provided through slip ring and brushes from dc supply. The excitation can be also made brushless with an ac exciter and a rotating bridge rectifier. Synchronous motor always runs at synchronous speed. The speed of the synchronous motor can be varied by varying the supply frequency, but if the speed is increased at constant voltage, because of the reduction in the air gap flux, the torque developed will be reduced.

The requirement of extra dc supply, slip rings and brushes discourage this type of motor for high performance applications (Stemmer 2009). Permanent Magnet (PM) synchronous motors are of more interesting the recent years. The stator winding of this motor is the same as that of WFSM, but the rotor winding is replaced by a permanent magnet. The advantage is the elimination of rotor loss, but at the same time the flexibility of field control is lost. PMSMs are more expensive than induction motors but have the advantage of higher efficiency (Bose 2006). PM synchronous motors are classified on the basis of the wave shape of induced emf as PM asynchronous motor (PMSM) and PM dc synchronous motor commonly known as brushless dc motor (BLDC).

PM dc synchronous motors have 15 %more power density than the PM ac synchronous motors. This is due to the fact that the ratio of the root mean square (RMS) value to peak value of flux density is higher in PM dc synchronous motors. Another major reason for the popularity of BLDC over PMSM is simplicity in control. In contrast to the PMSM which requires continuous and instantaneous absolute rotor position, the BLDC motor requires only six absolute position feedback for its control operation, resulting in major cost reduction in the feedback sensor (Krishnan2001).

III. SPEED CONTROL OF AC MOTORS DRIVES

The control and estimation of high power variable speed drives have gone through dynamic revolution over a long period of time. The advent of space vector theory of ac machines, advanced control estimation techniques, powerful digital signal processors, application specific integrated circuit (ASIC) chips, computer aided analysis, design and simulation tools and field programmable gate array (FPGA) have mainly contributed to these advancements. Fortunately, this control evolution has progressed in parallel with the advancement of power circuit elements such as high performance power semiconductor devices, multi-level converters and advance pulse width modulation (PWM) techniques. Modern artificial intelligent (AI) techniques, particularly neural network and fuzzy logic, are now advancing the frontier of ac drive technology (Bose 2011).Traditionally cage type induction motors have been the main workhorse for high power drives. For higher end of power, wound field synchronous motors are preferred because of efficiency considerations. In general, an ac drive can have one, two or four quadrant capability. They can perform torque, speed or position control in the primary loop or outer loop.

Also there are considerations of single and multi-motor drive, control accuracy, response time, robustness with load torque and parameter variation, sensor based and sensor less control, efficiency, reliability and line harmonics (Bose 1988).

IV. SYSTEM MODEL DESCRIPTION AND THE DYNAMIC ERROR SYSTEM

A. System Model Description

The mathematical model of a surface-mounted permanent magnet synchronous motor (SPMSM) drives can be described by the following equations in a dq synchronously rotating reference frame

$$\dot{\omega} = \frac{3}{2J}\frac{p^2}{4}\psi_m\, i_{qs} - \frac{B}{J}\omega - \frac{p}{2J}T_L$$

$$\dot{i}_{qs} = -\frac{R_s}{L_s}i_{qs} - \frac{\psi_m}{L_s}\omega + \frac{1}{L_s}V_{qs} - \omega\, i_{ds}$$

$$\dot{i}_{ds} = -\frac{R_s}{L_s}i_{ds} + \frac{1}{L_s}V_{ds} + \omega\, i_{qs}$$

where ω is the electrical rotor speed, ids and iqs are the d-axis and q-axis stator currents, Vds and Vqs are the d-axis and q-axis voltage inputs, Ls is the stator inductance, Rs is the stator resistance, ψm is the magnetic flux linkage, J is the moment of inertia, B is the viscous friction coefficient, p is the number of poles, and TL is the load torque. Depending on Rs, Ls, J,B, and ψm, the system parametersk1 − k6 can be denoted as

Then, the SPMSM drive system model is rewritten as the following equations:

$$k_1 = \frac{3}{2J}\frac{p^2}{4}\psi_m,\, k_2 = \frac{B}{J},\, k_3 = \frac{p}{2J}$$

$$k_4 = \frac{R_s}{L_s},\, k_5 = \frac{\psi_m}{L_s},\, k_6 = \frac{1}{L_s}.$$

B. Conventional PID Controller With Decoupling Term

First, the speed error (ωe) and rotor acceleration (β) are defined As

$$\omega_e = \omega - \omega_d$$

$$\beta = \dot{\omega} = k_1 i_{qs} - k_2\omega - k_3 T_L$$

Where ωd is the desired speed.From (3) and (4), the following dynamic equations can be Derived:

$$\dot{\omega}_e = \dot{\omega} - \dot{\omega}_d$$

$$\dot{\beta} = k_1(-k_4 i_{qs} - k_5\omega + k_6 V_{qs} - \omega i_{ds}) - k_2\dot{\omega} - k_3\dot{T}_L$$

$$\dot{i}_{ds} = -k_4 i_{ds} + k_6 V_{ds} + \omega i_{qs}.$$

In practical applications, the desired speed and the load torque vary slowly in the sampling period. Thus, it can be reasonably supposed that the derivatives of ωd and TL can be neglected.

Then, the system model (1) can be rewritten as

$$\dot{\omega}_e = \beta$$

$$\dot{\beta} = -k_2\beta - k_1 k_4 i_{qs} - k_1 k_5\omega - k_1\omega i_{ds} + k_1 k_6 V_{qs}$$

$$\dot{i}_{ds} = -k_4 i_{ds} + \omega i_{qs} + k_6 V_{ds}.$$

$$\ddot{\omega}_e + \lambda\dot{\omega}_e = -k_2\beta - k_1 k_4 i_{qs} - k_1 k_5\omega - k_1\omega i_{ds} + \lambda\beta$$

$$\dot{i}_{ds} = -k_4 i_{ds} + \omega i_{qs} + k_6 V_{ds}$$

Then, the second-order system can be achieved in the following:

$$u_{1f} = (k_1 k_4 i_{qs} + k_1 k_5\omega + k_1\omega i_{ds} + (k_2 - \lambda)\beta)\,/\,(k_1 k_6)$$

$$u_{2f} = (k_4 i_{ds} - \omega i_{qs})\,/k_6. \qquad ($$

Where λ is the positive control parameter. Based on the basic theory of the feedback linearization control, the decoupling control term uf = [u1f u2f] T is chosen as

$$\ddot{\omega}_e = -\lambda\dot{\omega}_e + k_1 k_6 (V_{qs} - u_{1f})$$

$$\dot{i}_{ds} = k_6 (V_{ds} - u_{2f}).$$

From (7) and (8), the dynamic error system can be formulated as follows:

Then, the conventional PID controller is given by

$$V_{dqs} = \begin{bmatrix} k_1 k_6 V_{qs} \\ k_6 V_{ds} \end{bmatrix} = B \begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = u_f + u_{\text{PID}}$$

Where B = dig [k1k6, k6], uf is the decoupling control term to compensate for the nonlinear factors, and u PID is the PID
Control term

$$u_{\text{PID}} = \begin{bmatrix} u_{1\text{PID}} \\ u_{2\text{PID}} \end{bmatrix} = \begin{bmatrix} -K_{1P}\omega_e - K_{1I}\int_0^t \omega_e dt - K_{1D}\dfrac{d\omega_e}{dt} \\ -K_{2P} i_{dse} - K_{2I}\int_0^t i_{dse} dt \end{bmatrix}$$
$$= EK \qquad (11)$$

Where (K1P), K2P), (K1I, K2I), and (K1D) are the proportional gains, integral gains, and derivative gain of the PID control term, respectively. The state and gain matrices are given as

$$E = \begin{bmatrix} \int_0^t \omega_e dt & \omega_e & \beta & 0 & 0 \\ 0 & 0 & 0 & \int_0^t i_{ds} dt & i_{ds} \end{bmatrix}$$

$$K = [-K_{1I} \quad -K_{1P} \quad -K_{1D} \quad -K_{2I} \quad -K_{2P}]^T.$$

It should be noted that the derivative of the stator current is normally very noisy; thus, it is not included in (11).

V. ADAPTIVE PID CONTROLLER DESIGN

The conventional PID controller (10) with the offline-tuned control gains can give a good control performance if the motor parameters (k1 to k6) are accurately known. However, the system parameters gradually change during operating time; therefore, after a long running time, the control performance can be seriously degraded if changed system parameters are not updated. To overcome this challenge, this section presents the adaptive tuning laws for auto adjustment of the control gains. On that note, the control gains, denoted as K1I, K1P, K1D, K2I, and K2P in (11), are adjusted to the proper values based on the supervisory gradient descent method. The proposed adaptive PID controller is assumed to have the following form:

$$V_{dqs} = u_f + u_{\text{PID}} - u_{\text{PID0}} + u_S$$

where uf is the decoupling control term which compensates for the nonlinear factors as shown in (6), u PID is the PID control term which includes the adaptive tuning laws, uS is the supervisory control term which guarantees the system stability, anduPID0 = EK0 (with K0 = [−K1I 0− K1P 0 −K1D0 −K2I 0−K2P 0]T is a constant coefficient matrix).

A. Proposed Adaptive PID Controller

In order to derive the proper adaptation laws, a new tracking error vector based on the reduced-order sliding mode dynamics is defined as

$$s(t) = \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} = \begin{bmatrix} \lambda\omega_e + \beta \\ i_{ds} \end{bmatrix}.$$

Then, the transfer function G (p) from s1 to ωe is given by the following strictly positive real function:

$$G(p) = \frac{\omega_e}{s_1} = \frac{1}{(\lambda + p)}$$

Where p is the Laplace variable. Hence, it can be concluded that ωe converges to zero as s→0.From the viewpoints of the SMC method, the sliding condition that ensures the hitting and existence of a sliding mode is deduced according to the Lyapunov stability theory. Commonly, the Lyapunov function candidate for the SMC is given by V1 = sT s/2. Then, the sliding condition can be obtained from the Lyapunov stability theory as

$$\dot{V}_1(t) = s^T \dot{s} < 0.$$

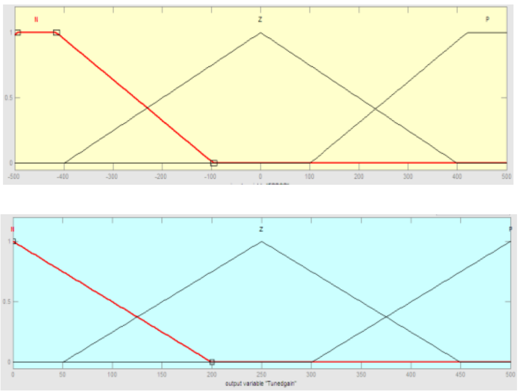
Fuzzy controller:

Fuzzy logic uses fuzzy set theory, in which a variable is member of one or more sets, with a specified degree of membership. Fuzzy logic allow us to emulate the human reasoning process in computers, quantify imprecise information, make decision based on vague and in complete data, yet by applying a "defuzzification" process, arrive at definite conclusions.

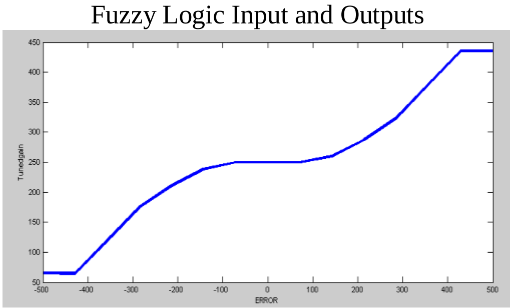
The FLC mainly consists of three blocks

- Fuzzification
- Inference
- Defuzzification

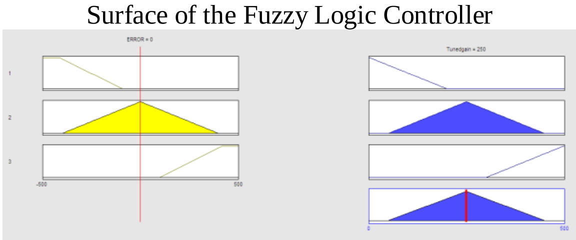
RULES:
If input is NEGATIVE then output is POSITIVE
If input is ZERO then output is ZERO
If input is POSITIVE then output is NEGATIVE



Fuzzy Logic Input and Outputs



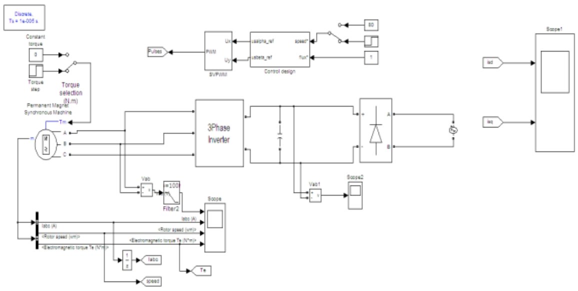
Surface of the Fuzzy Logic Controller



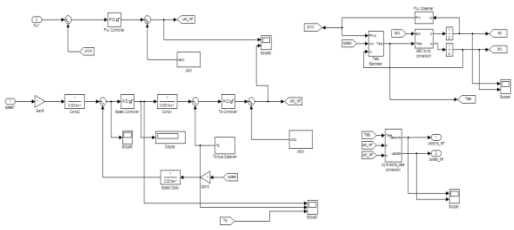
Rule Based of the fuzzy logic Controller

Mat lab/Simulation Results

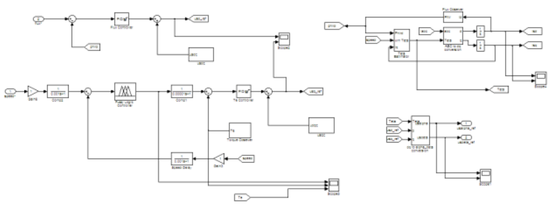
Mat lab is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include Math and computation Algorithm development Data acquisition Modeling, simulation, and prototyping Data analysis, exploration, and visualization Scientific and engineering graphics Application development, including graphical user interface building.



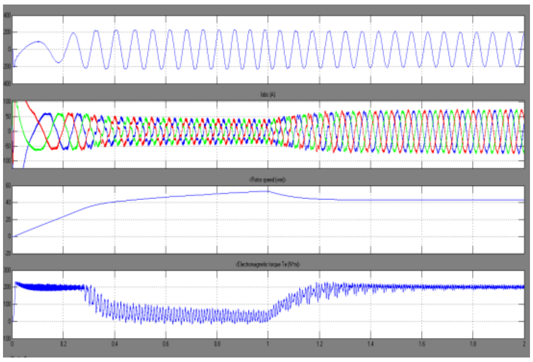
SIMULINK Model of the Proposed Method



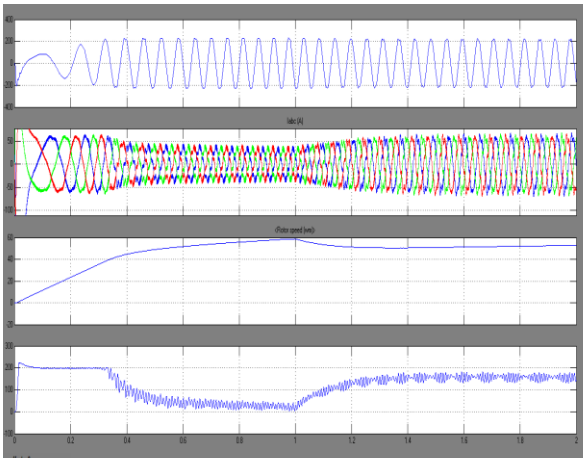
Control Design of the PID Controller



Control Design of the FL Controller



Output Results (VAB, Iabc, Speed, Torque) Using PID controller



Output Results (VAB, Iabc, Speed, Torque) Using Fuzzy

VI. CONCLUSION

In this paper, Fuzzy Logic control technique for velocity control of the PMSM drives was proposed. The proposed control calculation was straightforward and simple to actualize in the useful applications. By utilizing the inclination plummet strategy, the versatile tuning laws were proposed to auto modify the PID picks up that can accomplish positive following execution. In this manner, the proposed control plan could promise the precise and quick speed following disregarding the framework parameter varieties and outer burden unsettling influences. In addition, the strength investigation of the proposed control framework was portrayed in point of interest. To confirm the adequacy of the proposed control method, the Simulink Prototype was directed. For examination reason, the traditional PID controller was likewise tried at the same conditions as the proposed controller. It was confirmed through the Matlab Simulation that, the proposed Fuzzy Logic control could extensively improve the control execution contrasted with the routine PID control strategy.

These days, the exploration exercises are going ahead to build up the new investigation and tuning routines for the PID additions utilizing Intelligent Swarm Optimization Algorithms(Like PSO,GA,BBA) , so the proposed Fuzzy Logic control plan can help to lessen the troubles in these issues.

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