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Fuzzy Sliding-Mode Control for Speed Control for PMSM

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Abstract:

In order to optimize the speed-control performance of the permanent-magnet synchronous motor (PMSM) system with different disturbances and uncertainties, a nonlinear speed-control algorithm for the PMSM servo systems using sliding-mode con- trol and disturbance compensation techniques is developed in this paper. First, a sliding-mode control method based on one novel sliding-mode reaching law (SMRL) is presented.

This SMRL can dynamically adapt to the variations of the controlled system, which allows chattering reduction on control input while main- taining high tracking performance of the controller. Then, an ex- tended sliding-mode disturbance observer is proposed to estimate lumped uncertainties directly, to compensate strong disturbances and achieve high servo precisions. A fuzzy sliding mode controller is used to reduce the disturbances during loading. Simulation and experimental results both show the validity of the proposed control approach.

Index Terms:

Disturbance observer, permanent-magnet syn- chronous motor (PMSM), Sliding-mode control (SMC), sliding- mode reaching law (SMRL), fuzzy logic controller.

INTRODUCTION:

In the permanent-magnet synchronous motor (PMSM) control system, the classical proportional integral (PI) con- trol technique is still popular due to its simple implementa- tion [1]. However, in a practical PMSM system, there are large quantities of the disturbances and uncertainties, which may come internally or externally, e.g., unmodeled dynamics, pa- rameter variation, friction force, and load disturbances. It will be very difficult to limit these disturbances rapidly if adopting linear control methods like PI control algorithm [20].

Therefore, many nonlinear control methods have been adopted to improve the control performances in systems with different disturbances and uncertainties, e.g., robust control [4], [5], sliding-mode control (SMC) [6], [7], [10], [16], adaptive control [8], backstepping control [9], predictive control [11], in- telligent control [13], [14], and so on. In these nonlinear control methods, SMC method is well known for its invariant proper- ties to certain internal parameter variations and external distur- bances, which can guarantee perfect tracking performance de- spite parameters or model uncertainties. It has been successfully applied in many fields [15], [16].

In [6], the fuzzy sliding-mode approach was applied to a six-phase induction machine. In [7], a hybrid terminal sliding-mode observer was proposed based on the nonsingular terminal sliding mode and the high-order sliding mode for the rotor position and speed estimation in one PMSM control system.

In [17], the performance of a sliding- mode controller was studied using a hybrid controller applied to induction motors via sampled closed representations. The results were very conclusive regarding the effectiveness of the sliding-mode approach. A neuron-fuzzy sliding-mode controller applied to induction machine can also be found in [15].

However, the robustness of SMC can only be guaranteed by the selection of large control gains, while the large gains will lead to the well-known chattering phenomenon, which can excite high-frequency dynamics. Thus, some approaches have been proposed to overcome the chattering, such as continuation control, high-order sliding-mode method [16], complementary sliding-mode method [18], and reaching law method [2], [3], [12], [19]. The reaching law approach deals directly with the reaching process, since chattering is caused by the nonideal reaching at the end of the reaching phase.

In [3], authors pre- sented some reaching laws, which can restrain chattering by decreasing gain or making the discontinuous gain a function of sliding-mode surface. In [12], a novel exponential reaching law was presented to design the speed- and current-integrated controller.

To suppress chattering problem, system variable was used in this reaching law. However, in the aforementioned reach- ing laws, the discontinuous gain rapidly decreases because of variation of the functions of the sliding surface, thus reducing the robustness of the controller near the sliding surface and also increasing the reaching time.

In order to solve the aforementioned problems, a novel reach- ing law, which is based on the choice of an exponential term that adapts to the variations of the sliding-mode surface and system states, is proposed in this paper. This reaching law is able to deal with the chattering/reaching time dilemma. Based on this reaching law, a sliding-mode speed controller of PMSM is developed.

Then, to further improve the disturbance rejection performance of SMC method, extended sliding-mode disturbance observer (ESMDO) is proposed, and the estimated system disturbance is considered as the feedforward compensation part to compen- sate sliding-mode speed controller.

Thus, a composite control method combining an SMC part and a feedforward compen- sation part based on ESMDO, called SMC+ESMDO method, is developed. Finally, the effectiveness of the proposed control approach was verified by simulation and experimental result

PMSM Model:

One PMSM model in the rotor d–q coordinates can be expressed as follows

$$T_e = 1.5p\psi_a i_q$$

$$T_e - T_L = \frac{J}{p}\dot{\omega} + B\omega$$

$$u_d = ri_d - \omega L i_q + L\dot{i}_d$$

$$u_q = ri_q + \omega L i_d + \omega\psi_a + L\dot{i}_q$$

where ud and uq represent d and q axes stator voltages, respectively;id and iq are d and q axes currents, respectively; L isstator inductance; r is stator resistance; Te is electrical magnetictorque; TL is load torque; p is number of pole pairs; ψa is fluxlinkage of permanent magnets; ω is electrical angular velocity;B is viscous friction coefficient; J is rotational inertia.

SMC Design With Reaching Law Method:

Compared with other nonlinear control methods, SMC is more insensitive to internal parameter variations and external disturbance once the system trajectory reaches and stays on the sliding surface. However, how to design the SMC controller to reduce chattering is crucial, which motivates our researches for a new reaching law introduced in the next section. A complete study of SMRL theory can be found in [3]. In this section, the basicSMCdesign method is introduced briefly. In general, SMC design can be divided into two steps, the first step is to choose the sliding-mode surface, and the next step is to design the control input such that the system trajectory is forced toward the sliding-mode surface, which ensures the system to satisfy the sliding-mode reaching condition that is expressed as follows:

$$s \cdot \dot{s} < 0$$

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + g(x) + b(x)u \end{cases}$$

where x = [x1, x2]T is system state, g(x) represents the system

disturbances, and b(x) is not zero.
The concrete steps include the following. First, the typical sliding-mode surface is chosen as follows:

$$s_1 = cx_1 + x_2.$$

Such sliding-mode surface can guarantee the asymptotic stability of the sliding mode, and the asymptotic rate of convergence is in direct relation with the value of c. Next, the control input u should be designed in such a way that the sliding-mode reachingcondition (inequality (2)) is met. Thus, equal reaching lawis typically chosen as follows:

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$$\dot{s}_1 = -k_1 \cdot \operatorname{sgn}(s_1).$$

$$c\dot{x}_1 + \dot{x}_2 = -k_1 \cdot \operatorname{sgn}(s_1).$$

$$cx_2 + f(x) + g(x) + b(x) \cdot u = -k_1 \cdot \operatorname{sgn}(s_1).$$

$$u = -b^{-1}(x)[cx_2 + f(x) + g(x) + k_1 \cdot \operatorname{sgn}(s_1)].$$

$$-\omega + B\omega$$

Here, it can be found that the discontinuous term–b–1 (x) k1 •sgn
(s1) is contained in the control input, which leads to the occurrence of chattering. And the chattering level is up to the value of k1 directly.

DESIGN OF SMC SPEED CONTROLLER:

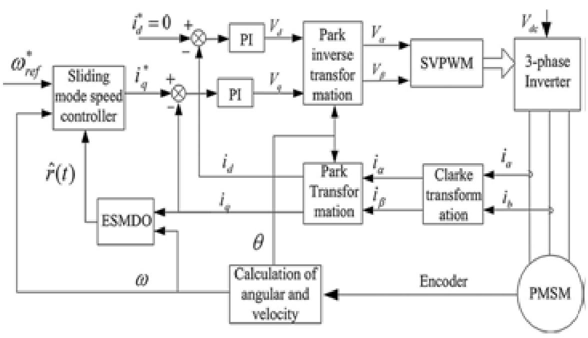
The novel SMRL is realized based on the choice of an exponential term that adapts to the variations of the sliding-mode surface and system states. This reaching law is given by

$$\dot{s} = -eq(x_1, s) \cdot \operatorname{sgn}(s), \quad eq(x_1, s) = \frac{k}{[\varepsilon + (1 + 1/|x_1| - \varepsilon)e^{-\delta|s|}]}$$

Speed Controller Design Based on the Proposed Reaching Law:

$$i_q^* = a_n^{-1}\{\dot{\omega}_{\text{ref}} + c_n\omega + [l + eq(x_1, S)] \cdot \operatorname{sgn}(S)\}.$$

Block digram:



SMC+ESMDO control scheme of the PMSM speed-regulation system.

Fuzzy system:

The fuzzy interface system Fuzzy system basically consists of a formulation of the mapping from a given input set to an output set using Fuzzy logic. The mapping process provides the basis from which the interference or conclusion can be made.

A Fuzzy interface process consists of following steps:

Step 1: Fuzzification of input variables.

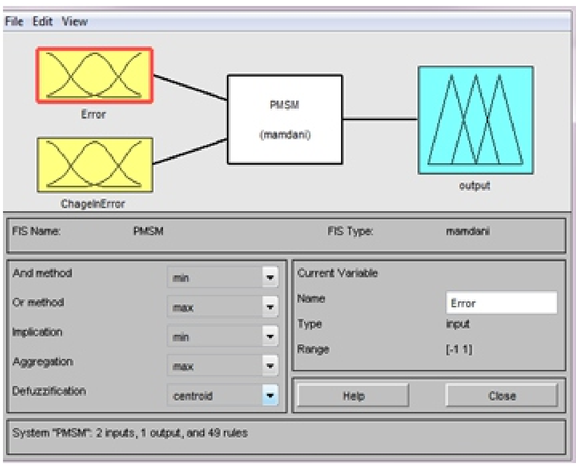
Step 2: Application of Fuzzy operator.(AND, OR, NOT) In the IF (antecedent) part of the rule.

Step 3: Implication from the antecedent to the consequent (Then part of the rule).

Step 4: Aggregation of the consequents across the rules.

Step 5: Defuzzification.

Generally there will be a matrix of rules similar tot eh ES rule matrix for Ex: There are 7MF for input variables 'x' and MF for input variable 'y' then there will be all together35 rules.



Fuzzy fis editor

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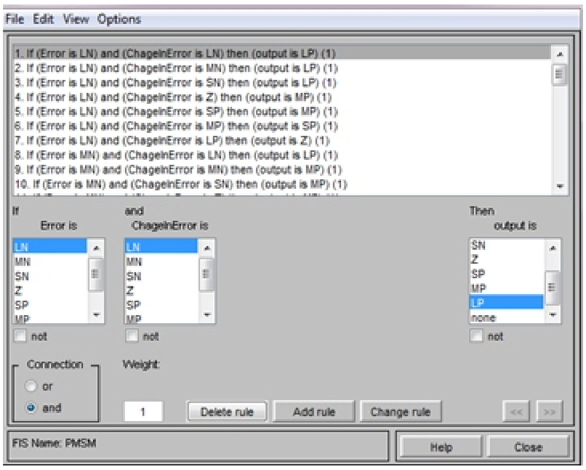


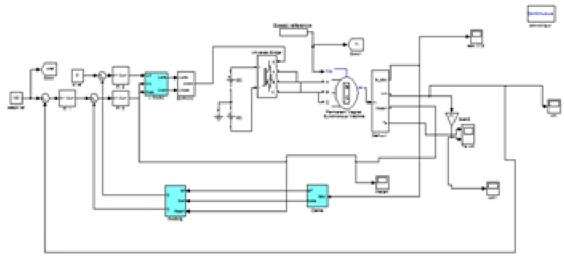
Fuzzy rules

Simulation Results:

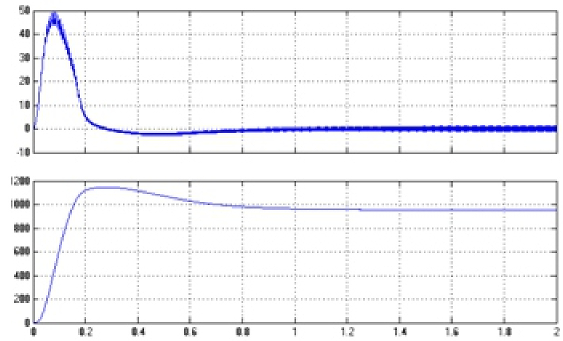
In this section, to demonstrate the effectiveness of the proposed
SMC+ESMDO approach, simulations, and experiments of the PI method and the SMC+ESMDO method in one PMSM system were made. Simulations are established in MATLAB/Simulink, and the experiments platform is constructed by TMS320LF2812 processor.

Simulation Results:

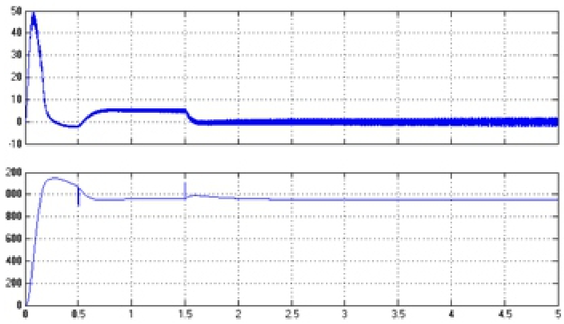
The PI simulation parameters of the both current loops are the same: the proportional gain Kpc = 10, the integral gainKic = 2.61. The PI simulation parameter of the speed loop is that proportional gain Kps = 0.5, and integral gain Kis = 20. The parameters of the SMC+ESMDO speed loop are: k = 20, δ = 10, ε = 0.1, and x1 = e. The simulation results of t PI controller and the SMC+ESMDO controller.From the simulation results, it can be observed that the SMC+ESMDO method has a smaller overshoot and a shorter settling timecompared with the PI method when the reference speed is 1000 r/min. Moreover, when load torque TL = 4 N • m is added suddenly at t = 0.1 s and removed at t = 0.2 s, the SMC+ESMDOmethod gives less speed and electrical magnetic torque fluctuations. Estimated load disturbance of the ESMDO and load disturbance command are shown in Fig. 9. It can be observed that the ESMDO can estimate the disturbance exactly and quickly with low chattering. A fuzzy smc controller is designed to reduce the transients during load conditions.



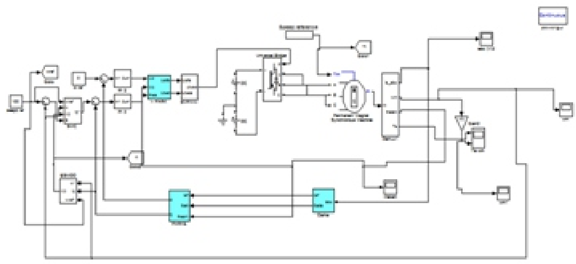
Simulation block of pmsm with pi controller.



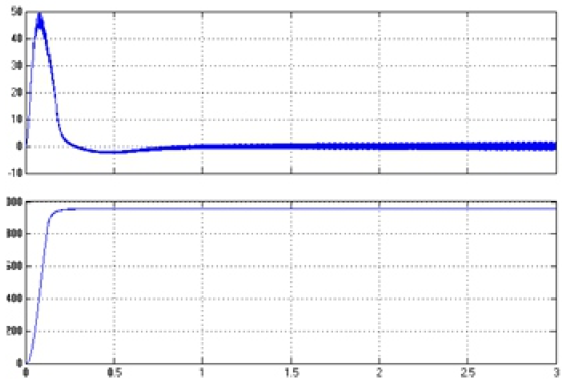
Simulation result with pi controller.



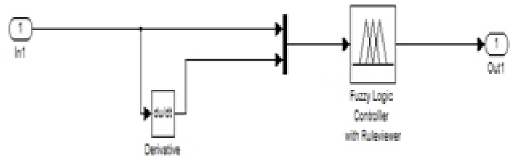
Simulation result with pi controller with change in load.



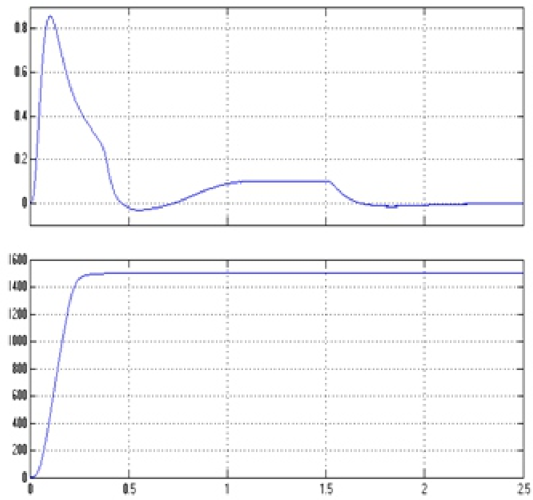
Simulation block of pmsm with SMC controller.



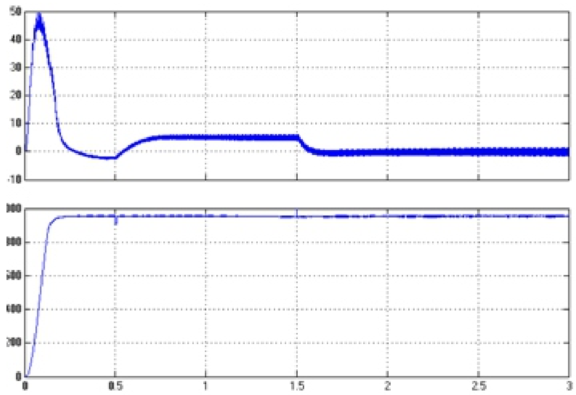
Simulation result with smc controller.



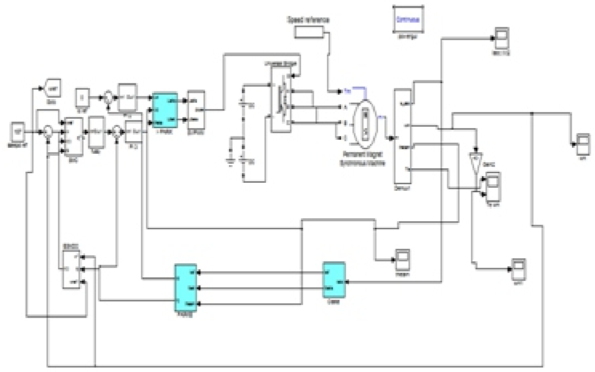
Fuzzy controller design.



Simulation result with smc fuzzy controller with change in load



Simulation result with smc controller with change in load



Simulation block of pmsm with SMC FUZZY controller

CONCLUSION:

In this project, one nonlinear SMC algorithm is proposed and has been applied to a PMSM system, to avoid chattering occurring and to suppress disturbances. The major contributions of this work include: 1) a novel SMRL method is introduced to control the chattering; 2) in order to estimate system disturbances, one extended sliding-mode disturbance observer is presented; and 3) a composite control method that combines SMC and ESMDO is developed to further improve the disturbance rejection ability of SMC system.4) A fuzzy SMC is designed to reduce the total distortion at any load values. Simulation results are done using MATLAB.

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