VARIABLES STRUCTURES THEORY USING TO SPEED CONTROL OF PERMANENT MAGNETIC SYNCHRONOUS MACHINE

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Key words: Permanent magnetic synchronous machine, sliding mode control, variable structure systems, motor drives.

ABSTRACT

In this paper variable structure theory (VSS) is proposed for high performance speed control of permanent synchronous motor (PMSM) drives. An improved cascade sliding mode control (CSMC) strategy is introduced first based on a modified control law in order to reduce chattering. It is then used in the CSMC system to improve system robustness and performance. The results show the superiority of the CSMC over a linear under load disturbance and parameter variations.

I. INTRODUCTION

Modern permanent synchronous motor (PMSM), due to their inherent advantages including high torque production, fast acceleration and high efficiency, have found widespread use in differs applications such as robotics, aerospace and electric vehicles. These high performance applications require complex still pratical methods. As it is well know by linear control theory, the design PI procedure consists in tuning their parameters in order to achieve the required bandwidth and disturbance rejection. A quite precise knowledge of motor and load parameters in thus required. This condition cannot be always satisfied because some parameters are not exactly known and/or are subjected to variation during operation.

As a consequence of these phenomena a degradation of the drive performance occurs. To avoid these problems, different non-linear control strategies have been proposed in the literature, such as adaptive control and variable structure control.

The theory of variable structure systems (VSS) has been extensively developed during the past 30years (Utkin1977) the most popular operation regime associated with VSS is known as sliding mode control (SMC). The main objective of this operation is to force the states to slide on prescribed surface called sliding surface. SMC is particularly useful in power systems with electronic actuators. Commonly, in these kinds of systems the chattering associated with the finite-switching frequency is not important, and SMC laws can be a suitable and extremely high performance option for its robustness against model uncertainties, parameters variations and external disturbances. Others remarkable advantages of this control approach are the simplicity of its implementation and the order reduction of the closed loop system.

In this paper a cascade sliding mode control (CSMC) system is proposed for PMSM drives to enhance system robustness against motor parameter variations and load disturbances. In order to reduce the problem of chattering phenomenon, smooth control functions with appropriate threshold have been chosen.

II. ACTUATOR MODELING

In order to model the PMSM we make some classical hypotheses as the spatial distribution of the stator winding is sinusoidal, the the saturation and the damping effect is neglected. Using this hypotheses the machines modeling can be made in Park's d-q frame. The electrical equation are:

$$\begin{aligned} v_d &= R\, i_d + L_d \frac{di_d}{dt} - L_q\, \omega i_q \\ v_q &= R\, i_q + L_q \frac{di_q}{dt} + L_d\, \omega i_d + \phi_f\, \omega \end{aligned} \qquad (1)$$

$$\begin{aligned} \phi_d &= L_d i_d + \phi_f \\ \phi_q &= L_q i_q \end{aligned} \qquad (2)$$

The dynamic behavior and electromagnetic torque are given by :

$$C_{em} = p((L_d - L_q) i_{qs} i_{ds} + \phi_f i_{qs}) \qquad (3)$$

$$J\frac{d\omega}{dt} + f\omega = C_{em} - C_r \qquad (4)$$

Equations (1) to (4) yield the bloc diagram of figure 1

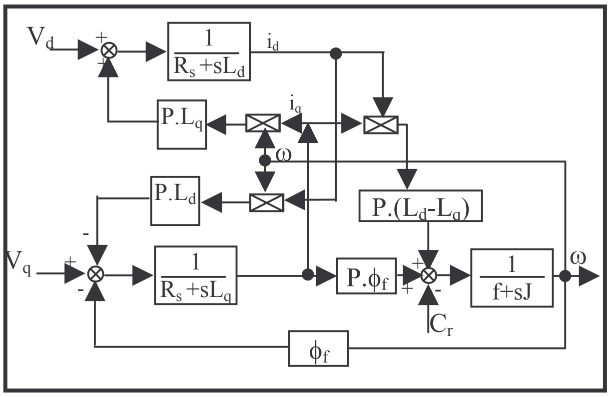

Figure 1 Diagram of PMSM model

III. SLIDING MODE CONTROL THEORY

VSS differs from other control systems in that it changes its control structure discontinuously. In the usual control systems, the control structures are fixed in the process of controller, even through the coefficients are changed continuously according to the adaptation systems mechanism. The same structures are preserved through the control process. The control actions provide the switching between subsystems, which give a desired behavior of the closed loop system. [5,6,7]

Let us consider the following dynamic in which the control enters linearly:

$$\frac{dx}{dt} = f_i(t, x_1, x_2, x_3, \ldots x_n) \quad \text{avec } i = 1,2,3,\ldots n \tag{5}$$

Where x = (x1 , x2 , x3, …xn) and S(x) is the switching surface. The variable structure systems is a nonlinear system in which slinding mode occurs on a switching surface Si(x,t)=0; when all of the trajectories are attracted to the subspace Si =0.Then the state of the system slides and remains on the surface $S(t, x_1, x_2, x_3, \ldots x_n) = 0$. A well-known surface chosen to obtain a sliding mode regime, which guarantees the convergence of the state x to its reference x_{ref} is given as following by JJ Slotine [2,4,6]:

$$S(x) = \left(\frac{d}{dt} + \lambda\right)^{r-1}(x_{ref} - x) \tag{6}$$

Where r is the degrees of the sliding surface and λ a positive constante.

Two parts have to be distinguished in the control design procedure. The first one concerns the attractivity of the state trajectory to the sliding surface and the second represents the dynamic response of the representative point in sliding mode. One can chose for the controller the following expression:

$$u(t) = u_{eq}(t) + u_n \tag{7}$$

Where u_{eq} is the control function defined by Utkin, and noted equivalent control as shows in figure 2 . For which the trajectory response remains on the sliding surface [1,2].

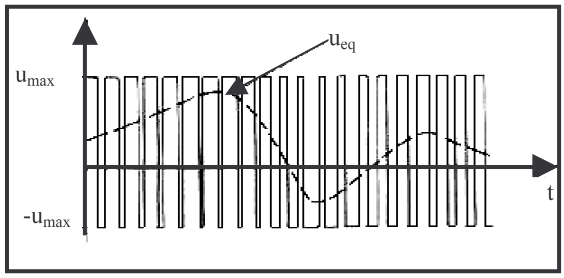

Figure 2 Equivalente Control

In this case, the invariance condition is expressed as:

$$S_i(x) = 0. \quad \text{and} \quad \dot{S}_i(x) = 0. \tag{8}$$

In the system described by equation 5, when the SM is arise, the dynamic of the system in SM is subjected to the following equation $S_i(x)=0$. Thus for the ideal SM we have also $\dot{S}_i(x)=0$.

$$\frac{dS_i}{dt} = \dot{S}_i = 0 \qquad \Lambda\frac{dS_i}{dt}\frac{dx}{dt} = 0 \tag{9}$$

The term of u_n is added to global function of the controller in order to guarantee the attractiveness of the chosen sliding surface. This later is achieved by the condition:

$$S(x)\dot{S}(x) < 0 \tag{10}$$

$$U_n = K.\ \mathrm{sgn}(S(x)) \tag{11}$$

However, this later produces a drawback in the performances of a control system, which is known as chattering phenomenon.

The used approach to reduce chattering phenomena was to introduce a boundary layer around the sliding surface and to use a smooth function to replace the discontinuous part of the control action as follows [6,7].

Thus, the controller become as shown in figure 3.

$$\begin{aligned} u_n &= 0 && \text{si } |S(x)| < \varepsilon_1 \\ u_n &= K \,\mathrm{sign}(S(x)) && \text{si } |S(x)| > \varepsilon_2 \\ u_n &= \frac{K}{\varepsilon_1 - \varepsilon_2}\,\mathrm{sign}(S(x)) && \text{si } \varepsilon_1 < |S(x)| < \varepsilon_2 \end{aligned} \tag{12}$$

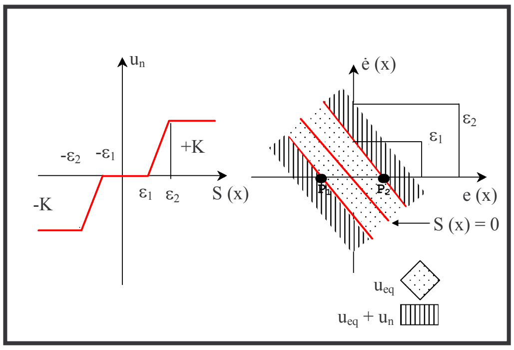

Figure 3 Sliding mode with boundary layer and the modified switching law

Where the constant K takes admissible value. It is linked to the speed of convergence towards the sliding surface of the process (the reaching mode). Compromise must be made when choosing this constant, since if K is very small the time response is important and the robustness may be lost, whereas when K is too big the chattering phenomenon increases.
And ε_1, ε_2 are the seuil using to adducing the control.

IV. SMC using to speed control of PMSM:

The SMC is applied to PMSM model, in such a way to obtain simple surfaces. Figure 4 shows the proposed control scheme in a cascade form in which three surfaces are required. The internal loop allows controlling the direct current id, whereas the external loop provides the speed regulation which assure the transverse current reference.

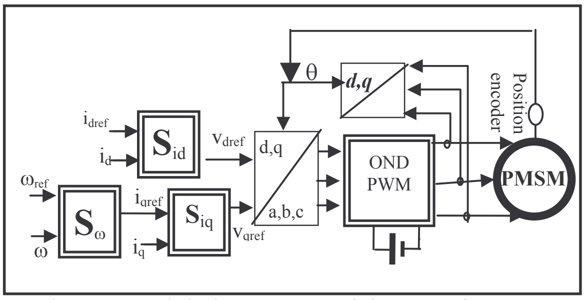

Figure 4: Global structure of the use of CSMC to PMSM speed regulation

The sliding surface for each loop is chosen as follows:

DİRECT CURRENT REGULATİON

When the current error e_d is:

$$e_d = i_{dref} - i_d$$

The surface is deduced from the equation (8) here the degrees of the sliding surface r equal to 1 so that one obtain:

$$S(i_d) = i_{dref} - i_d \qquad (13)$$

Using equations 8 et 9 it follows:

$$\dot{S}(i_d) = i_{dref} + \frac{R}{L_d} - p\frac{L_q}{L_d} i_q \omega - \frac{1}{L_d} u_d \qquad (14)$$

When the sliding mode is occurrence the surface $S(i_d)$ became null also its derivative

$$\dot{S}(i_d) = 0$$

$$u_{deq} = \left(\frac{di_{dref}}{dt} + \frac{R}{L_d} i_d - p\frac{L_q}{L_d} i_q \omega\right) L_d \quad \text{et} \quad u_{dn} = 0 \qquad (15)$$

During the convergence mode we have to satisfies the condition $S(x)\dot{S}(x) < 0$ by choosing

$$u_{dn} = K_d \operatorname{sgn}(S(i_d))$$

So that it result the output command of the direct current as

$$u_{dref} = u_{deq} + u_{dn}$$

$$u_{dref} = \left(\frac{di_{dref}}{dt} + \frac{R}{L_d} i_d - p\frac{L_q}{L_d} i_q \omega\right) L_d + K_d \operatorname{sgn} S(i_d) \qquad (16)$$

SPEED REGULATION

When the speed error e_ω is:

$$e_\omega = \omega_{ref} - \omega$$

The surface is deduced from the equation (8) here the degrees of the sliding surface r equal to 1in order to evaluate the current reference so that one obtain:

$$S(\omega) = e_\omega \qquad (17)$$

Applied Emilianov and Utkin function it follows:

$$\dot{S}(\omega) = \omega_{ref} - \left[\frac{p(L_d - L_q)}{J} i_d + \frac{P\varphi_f}{J}\right] i_q + \frac{f}{J}\omega \qquad (18)$$

During the convergence mode we have to satisfies the condition $S(\omega)\dot{S}(\omega) < 0$ by choosing

$$i_{qn} = k_\omega \operatorname{sgn}(S(\omega)) \qquad (19)$$

So that it result the output command of the transverse current is:

$$i_{qref} = \frac{\frac{f}{J} + \frac{1}{J} Cr + \omega_{ref} + K_q \operatorname{sgn}(S(\omega))}{\frac{R}{L_d} i_d + p\frac{L_d}{L_q}} \qquad (20)$$

TRANSVERSE CURRENT REGULATION

Here the degrees of the sliding surface r equal to 1 so that one obtain:

$$S(i_q) = e_q \qquad (21)$$
$$e_q = i_{qref} - i_q$$

Using equations 8 et 9 it follows:

$$\dot{S}(i_q) = \dot{i}_{qref} + \frac{R}{L_q} i_q - p\frac{L_d}{L_q} i_d\omega - \frac{1}{L_q} v_q \qquad (22)$$

During the convergence mode we have to satisfies the condition $S(i_q)\dot{S}(i_q)<0$ by choosing

$$U_{qn} = K_q \, sgn(S(i_q)) \qquad (23)$$

So that it result the output command as

$$u_{qref}=\left(\frac{di_{qref}}{dt}+\frac{R}{L_d}i_q-p\frac{L_q}{L_d}i_d\omega\right)L_q+K_q sgnS(i_q) \qquad (24)$$

V. SIMULATION RESULTS

the different coefficients using to eliminate chattering phenomena are as follow:
$K_\omega = 10$, $\varepsilon_{1\omega} = 1$, $\varepsilon_{2\omega} = 3$, $K_d = 15$, $\varepsilon_{1d} = 0.01$, $\varepsilon_{2d} = 0.02$
$K_q = 20$, $\varepsilon_{1q} = 0.01$, $\varepsilon_{2q} = 0.02$

A cascade structure with SMC of the PMSM was simulated as described below. Figure 5 presents the dynamic responses of the system when we introduce a step speed reference and direct current references. A load torque (5Nm) is imposed at t = 0.2secto t= 0.4sec. It clearly shown that the input reference is perfectly attracted by the speed and the introduced perturbation is immediately rejected by the control system.

The inversion test gives rise to rapid speed response, which gives evidences of the regulation.
In figure 6 shows transit response on step change of speed under various values of the moment of inertia J. And figure 7 illustrates the transit response on step change of speed under various values of the resistance R; the controller leads to required equal wave form of speed change, without overshoot and chattering, that in order to test the CSMC performance.
The robustness of the control system is achieved by the SMC and the cascade structure used. The comparison of the CSMC and PI regulator is shown in figure 8 , this results confirm the robustness quality inherent to the proposed controller.

V. CONCLUSION

The paper deals with the robust speed control of PMSM using the variable structure systems theory. The performance of the sliding mode chosen was verified by simulation .
The SMC is unfeeling to parameters variation, such as the moment of inertia and load torque.
The chattering phenomenon is been successfully eliminated from speed control. The effectiveness of the proposed control system was proved by comparison with simulation results of the conventional regulator (PI).

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PMSM parameters:

Machine of 2 KW, 220V, 8A, 4000tr/min
R: stator resistance (0.76Ω)
L_d, L_q: longitudinal and transversal inductance in Park's system (1.7mH, 1.8mH).
J: moment of inertia ($0.0011 Kg.m^{-3}$)
f: coefficient of friction($5.10^{-5} Nm/rads^{-1}$)
ϕ_f: permanent magnet flux (0.140Wb)
P : number of pole pairs (2).
Ω :rotor angular speed
C_{em}: electromagnetic torque, C_r: load torque
ϕ_d, ϕ_d : PM flux through the stator winding in park's frame.

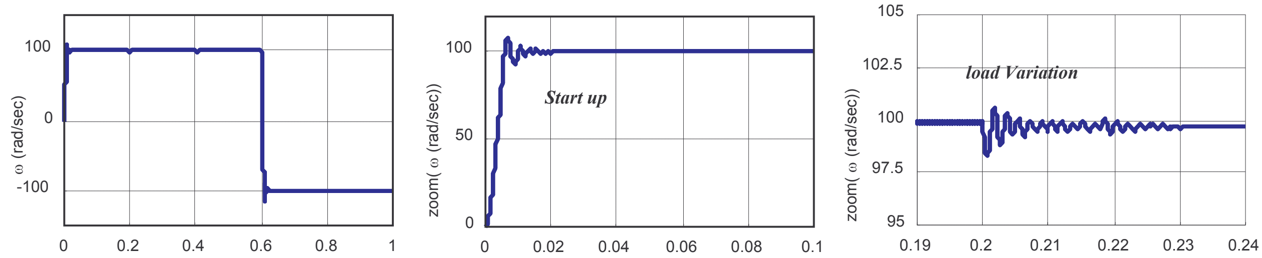

Fig 5. Response system with CSMC

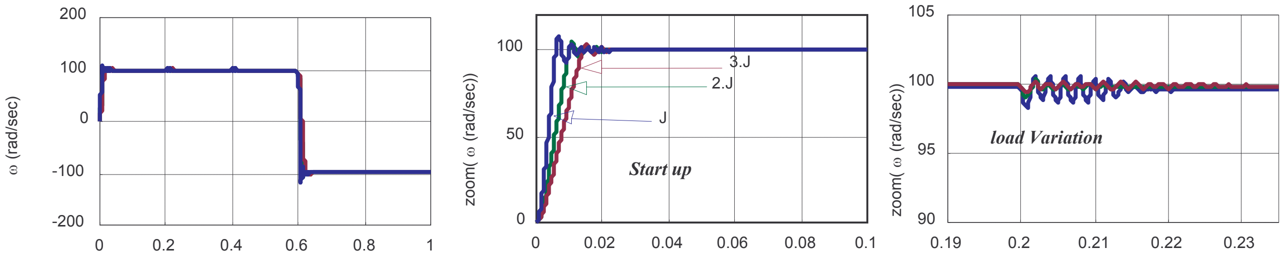

Fig .6 Response system with CSMC under inertia moment variation J

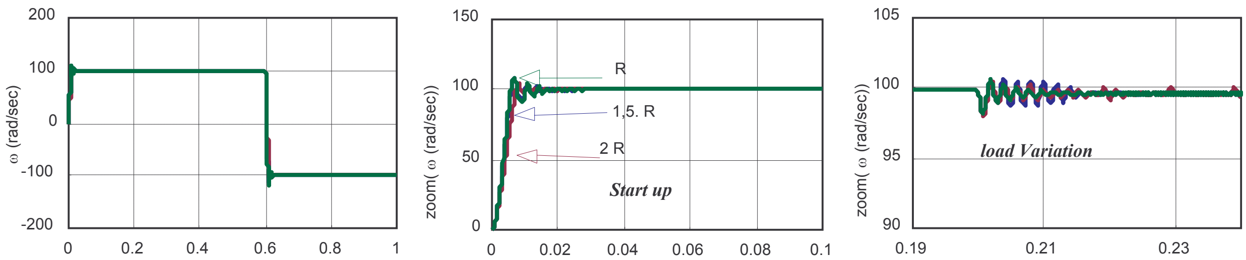

Fig.7 Response system with CSMC under statorique resistance R variation

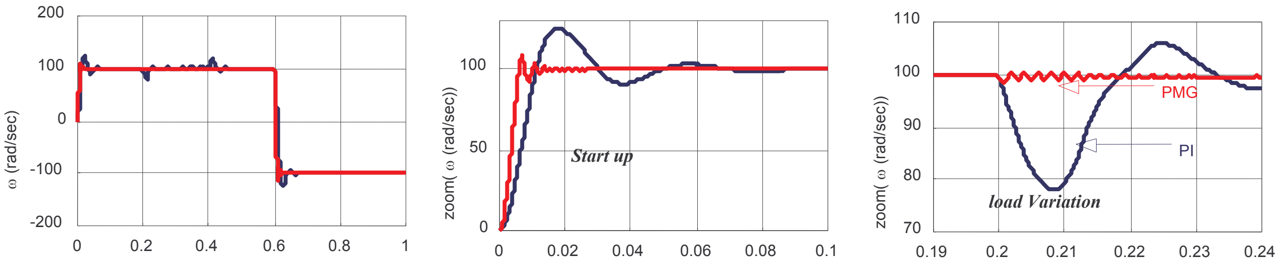

Fig.8 Comparison between CSMC and classical regulator PI