Speed control of Permanent
Magnetic Synchronous Machine using Sliding mode controller.

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Abstract:
Since many years the use of the permanent magnetic synchronous machine (PMSM) in variable speed application shows notable characteristics. This paper deals with the robust speed control of PMSM using variable structure systems theory and particularly the sliding mode control (SMC). Application of conventional regulators applied to PMSM fed by a PWM voltage source inverter has been studied and compared to the sliding mode control. Simulation study is conducted to show the effectiveness of the proposed method. The obtained results showed that the (SMC) control increases the robustness of the system under parameter variations and external disturbances. A set of simple surfaces have been applied to a cascade structure and associated control laws have been synthesized Furthermore, in order to reduce chattering phenomenon, smooth control functions with appropriate threshold have been chosen.

Key words: field oriented control, PMSM, sliding mode control, PI regulator.

Introduction:

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 or sliding manifold. SMC is particularly useful in power systems with electronic actuators. Commonly, in this 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 first the conventional control is applied to PMSM. Secondly the SMC approach is described briefly and the plant model of PMSM is given in the form suited for the SMC finally the design procedures are shown in detail with the simulations results.

I Actuator modeling:

In order to model the PMSM we make some classical hypotheses:

Spatial distribution of the stator winding is sinusoidal.
The saturation is neglected.
The damping effect is neglected.
Using this hypotheses the machines modeling can be made in Park's d-q frame. The electrical equation are:

$$\begin{cases} v_{ds} = R_s i_{ds} + \dfrac{d\phi_d}{dt} - \omega\phi_q \\ v_{qs} = R_s . i_{qs} + \dfrac{d\phi_q}{dt} + \omega\phi_d \end{cases} \quad \ldots(1)$$

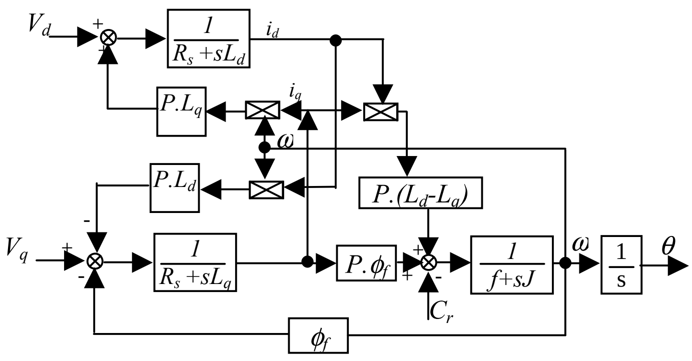
$$\begin{cases} \phi_d = L_d i_{ds} + \phi_f \\ \phi_q = L_q i_{qs} \end{cases} \quad \ldots(2)$$

the dynamic behavior and electromagnetic torque are given by :

$$C_{em} = p(\phi_d i_{qs} - \phi_q i_{ds}) \quad \ldots(3)$$

$$J\frac{d\Omega}{dt} + f_c\Omega = C_{em} - C_r \quad \ldots(4)$$

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



Fig(1) diagram of PMSM model

II Field oriented control strategy:

The control strategy is based upon a decoupling of the two axes through an approach state feedback. Since in the d, q frame, the field oriented control (FOC) is achieved when i_d is equal to zero.

$$\begin{cases} v_{ds} = -L_q \omega i_{qs} \\ v_{qs} = R_s i_{qs} + L_q \dfrac{di_{qs}}{dt} + \phi_f \omega \end{cases} \qquad \ldots(5)$$

$$C_{em} = p\,\phi_f\, i_{qs} \qquad \ldots(6)$$

So that the block diagram of the actuator reduces to that of figure (2) which is equivalent to direct current machine.

III.1 Speed control using PI regulator:

Figure (3) shows the general view of the control system. The PI regulator choice contributes to find the decoupling quality between the two axis (d, q). The quadrate current reference i_q^* is provided by a speed PI regulator; the reference limitation prevent the torque to exceeds the fixed maximal value. At closed loop the system characteristics equation is identified to desire one and it results the differences regulators with their specific transfer function ($K_p + \frac{K_i}{s}$) as shown in figure (3.a,b).

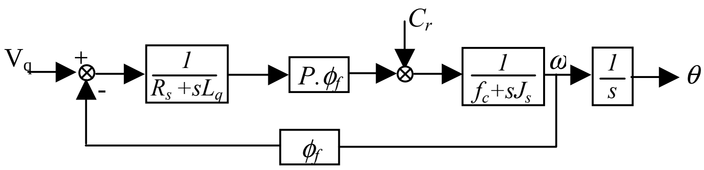


Fig.(2) simplified model of PMSM

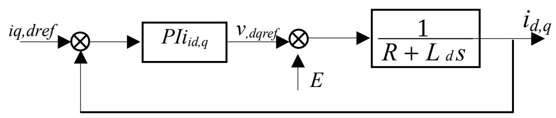


Fig.(3.b) current regulator

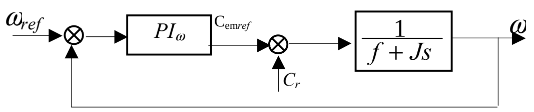


Fig.(3.b) speed regulator

The differences coefficients are :

$(PI)_\omega$: $K_p = 0.2,\ K_i = 10$

$(PI)_{id}$: $K_p = 1.2,\ K_i = 400$

III 2 Simulation results:

The simulation of the PMSM speed control with the PI regulators is realized using matlab – simulink environment.

In figure (6.a), during starting up period, the commanded torque equals the maximum capability of the machine. This ensures that the machine runs up in the shortest time.

A load of 5 Nm is applied to the motor between t = 0.2 sec and t = 0.4 sec, this causes a small decrease in the speed.

The inversion test gives rise to rapid speed response with a little surpassing, which gives evidences of the regulation.

In figure (6.b) shows the influence of the moment of inertia change on the regulator performance. The increasing of J causes a surpassing of the speed and the decoupling of the machine is lightly affected by this changing so, for the use which require the precision the regulator loss his robustness.

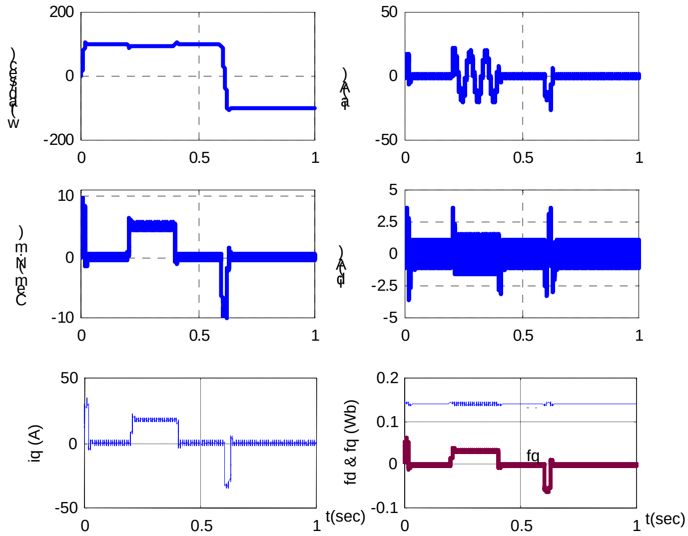


Fig.(6.a) response of the system with the PI regulator

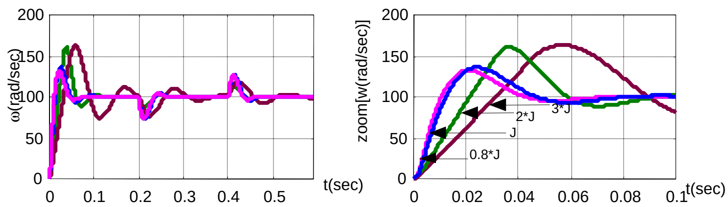


Fig. (6.b) robustness test of PI regulator for different values of moment of inertia J

IV .1 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:

$$\dot{x} = f(x,t) + B(x,t).u \ldots(7)$$

Where the $x, f \in R^n$, $B(x,t)$ is an n x m matrix the dimensional control is u has the following discontinuous function:

$u_i(x,t)=u^+(x,t)$ si $S_i(x)>0$ pour i=1,2,3,...m

$u_i(x,t)=u^-(x,t)$ si $S_i(x)<0$ pour i=1,2,3,...m

u_i^+ u_i^- are the continuous functions.

S(x) is the switching surface.

The variable structure systems is a nonlinear system in which every component of the vector control *u* can be equal to two continuous functions of the state space. SM occurs on a switching surface $S_i(x,t)=0$; when all of the trajectories are attracted to the subspace $S_i=0$.

Figure (6) illustrates a sliding phenomenon

Fig (6) State trajectory in SMC

Then the state of the system slides and remains on the surface $S_i(x,t)=0$

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]:

$$S(x)=\left(\frac{d}{dt}+\lambda\right)^{r-1}(x_{ref}-x) \quad \ldots(8)$$

Where r is the degrees of the sliding surface.

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:

$$u_i=u_{ieq}+u_{in} \quad \ldots(9)$$

Where U_{eq} is the control function defined by Utkin, and noted equivalent control. For which the trajectory response remains on the sliding surface [bulher]. In this case, the invariance condition is expressed as:

$$S_i(x)=0. \quad \text{and} \quad \dot{S}_i(x)=0. \ldots(10)$$

In the system described by equation (7), 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 $\dot{S}_i(x)=0.$

$$\frac{dS_i}{dt}=\dot{S}_i=0$$

$$\Lambda\frac{dS_i}{dt}\frac{dx}{dt}=0 \qquad L=\frac{dS}{dx} \quad \ldots(11)$$

$$L.f(x,t)+L.B(x,t).(u_{eq}+u_n)=0 \quad \ldots(12)$$

$$u_{eq}=-(L.B)^{-1}.L.f \quad \ldots(13)$$

U_{eq} can be represented as the average value of the control switching representing the successive commutation in the range [U_{min}. U_{max}] as show in figure (7).[5,6]

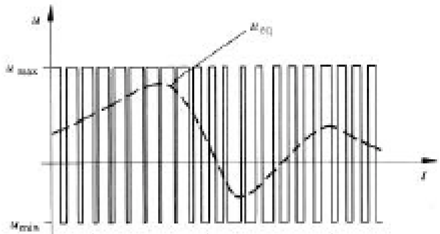


Fig (7) U_{eq} interpretation

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:

$$S(x)\dot{S}(x)<0 \quad \ldots(14)$$

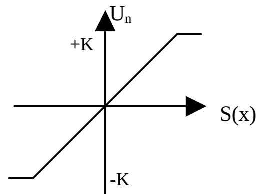
$$U_n=K.\ sgn\ (S(x)) \quad \ldots(15)$$

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

In order to reduce this phenomenon due to the discontinuous nature of the controller, a smooth function replaces the discontinuous part of the control action. Thus, the controller becomes figure (8):

$$U_n=\begin{cases}0 & \text{if } |S(x)|<0\\ K\text{sgn}(S(x)) & \text{if } |S(x)|>0\end{cases} \quad \ldots(16)$$

Where K takes admissible value.



Fig(8) commande continuos U_n

IV .2 Application to speed control of PMSM:

The SMC is applied to PMSM model, in such a way to obtain simple surfaces. Figure(9) shows the proposed control scheme in a cascade form in which two surfaces are required. The internal loop allows controlling the direct current id, whereas the external loop provides the speed regulation.

The sliding surface for each loop is chosen as follows:

1- Direct current regulation:

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:

$$S(i_d)=i_{dref}-i_d \quad \ldots(17)$$

Using equation (5,10, 16) it follows:

$$\dot{S}(i_d)=i_{dref}+\frac{R}{L_d}-p\frac{L_q}{L_d}i_q\Omega-\frac{1}{L_d}u_d \quad \ldots(18)$$

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

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

$$\Rightarrow u_{deq}=(\frac{di_{dref}}{dt}+\frac{R}{L_d}i_d-p\frac{L_q}{L_d}i_q\Omega)L_d \quad et \quad u_{dn}=0 \quad \ldots(19)$$

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

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

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

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

$$u_{dref}=(\frac{di_{dref}}{dt}+\frac{R}{L_d}i_d-p\frac{L_q}{L_d}i_q\Omega)L_d+K_d\,\mathrm{sgn}S(i_d)\quad ..(20)$$

2- Speed regulation:

One write state equation for this variable as follow (deduced from equations 1,3,4):

$$\dot{\Omega}=(\frac{p(L_d-L_q)}{J}i_d+\frac{P\phi_f}{J})i_q-\frac{f}{J}\Omega \qquad \ldots(21)$$

The surface is deduced from the equation (8) here the degrees of the sliding surface r equal to 2 so that one obtain:

$$S(\Omega)=\dot{e}_\Omega+\lambda_\Omega e_\Omega \ldots(22)$$

With
$$e_\Omega=\Omega ref-\Omega$$
$$\dot{e}_\Omega=\dot{\Omega} ref-\dot{\Omega}$$

As result the surface derivative is :

$$\dot{S}(\Omega)=\ddot{e}_\Omega+\lambda_\Omega \dot{e}_\Omega \ldots(23)$$

the condition to satisfy the sliding mode is when the surface $S(I_d)$ became null also its derivative

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

That gives the commanded voltage u_{qeq}:

$$u_{qeq}=i_q i_d\frac{p(Ld-Lq)}{J}-(iq\frac{R}{Lq}-P\Omega(id\frac{Ld}{Lq}-\frac{\phi_f}{Lq}))(\frac{p(Ld-Lq)}{J}id+\frac{\varphi_f}{J})+\frac{J}{J}\ldots \quad \ldots(24)$$

Where $u_{qref} = u_{qeq} + u_{qn}$

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

$$U_{qn} = K_q \, sgn\,(\,S\,(\Omega)\,)$$

So that it result the output command of the speed control is:

$$u_{qref}=u_{qeq}+K_q\,\mathrm{sgn}S(\Omega) \qquad \ldots(25)$$

3- Simulation results:

A cascade structure with SMC of the PMSM was simulated as described below, using the same condition with the PI regulator.

Figure (10.a) 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 = 0.2sec ÷ 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 (10.b) shows transit response on step change of speed under various values of the moment of inertia J. the controller leads to required equal wave form of speed change, without overshoot and chattering, that in order to test the SMC performance.

The robustness of the control system is achieved by the SMC and the cascade structure used.

The comparison of the SMC and Pi regulator is shown in figure (11), this results confirm the robustness quality inherent to the proposed controller.

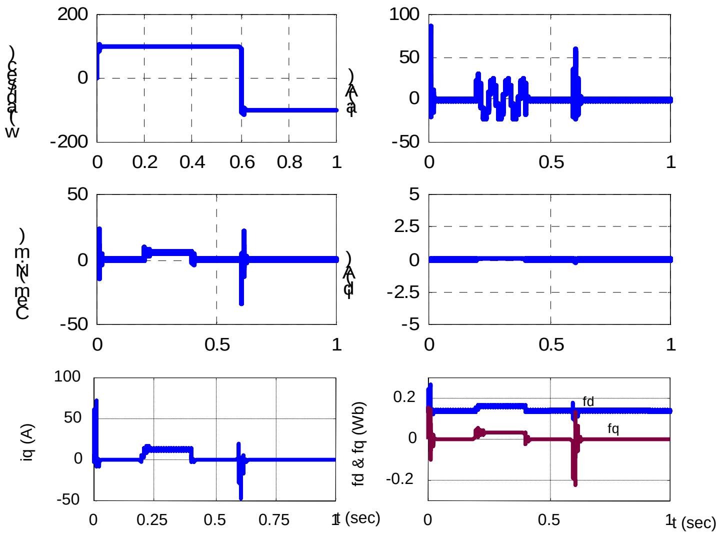


Fig.(10.a) response system using SMC

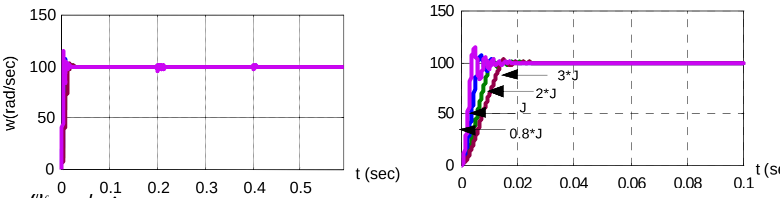
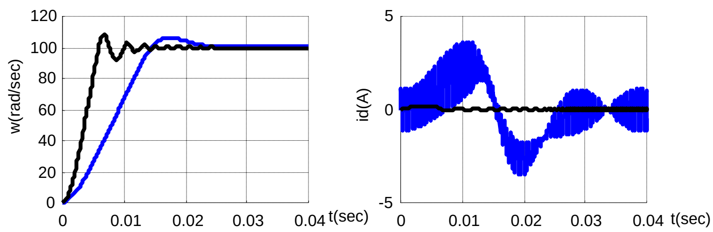
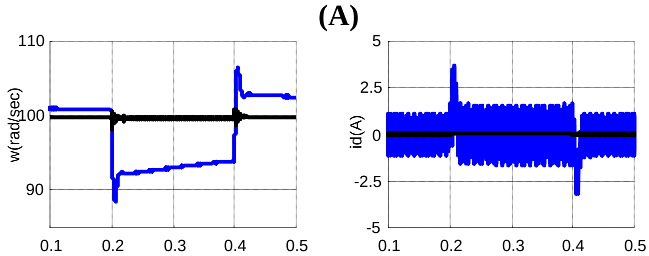


Fig.(10.b) robustness test of SMC for different values of moment of inertia J

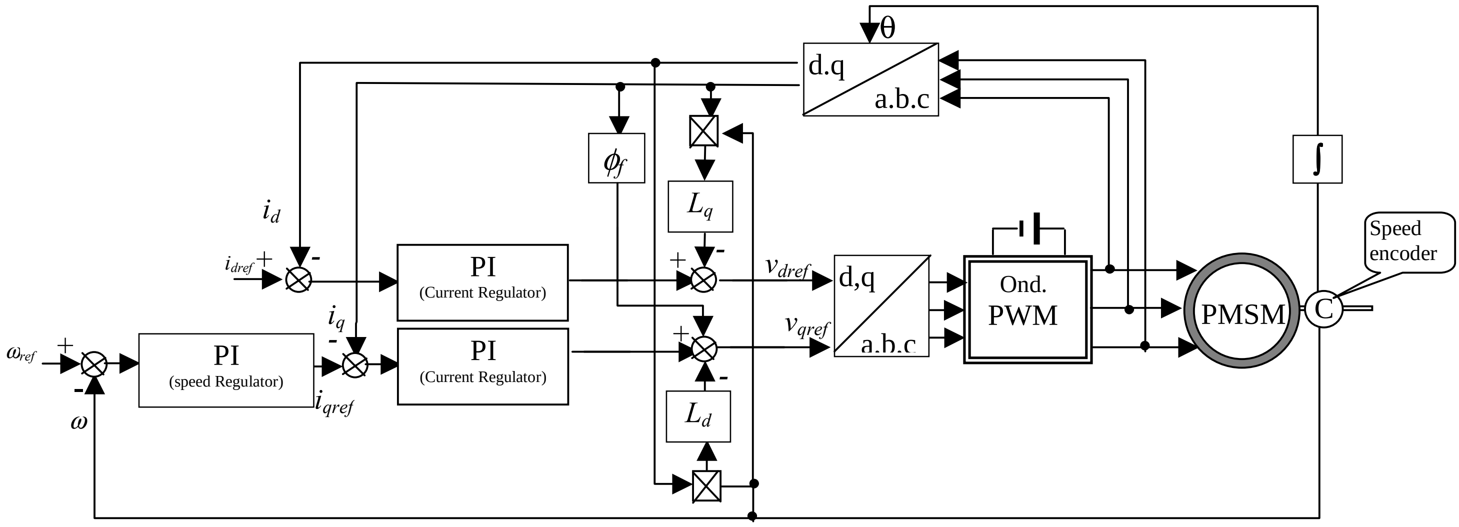


(A)

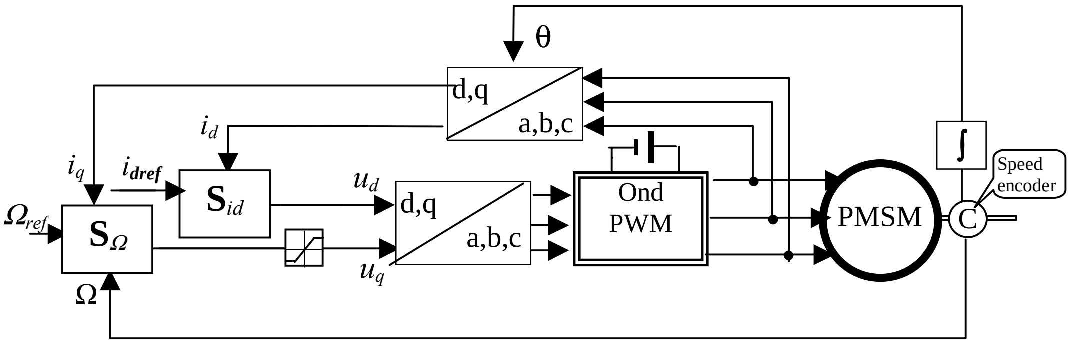


(B)

Fig.(11) comparison result of SMC and PI
(A) Start up
(B) Load variation



Fig(5) PMSM Speed regulation with field oriented control using PI regulators



Fig(10) block diagram of Speed regulation of PMSM using SMC

Conclusion:

The paper deals with the robust speed control of PMSM using the variable structure systems theory particularly sliding mode control.
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 simulation results and their comparison with conventional regulator (PI).

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 (0.0011Kg.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.

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