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FLUX-WEAKENING CONTROL OF PERMANENT MAGNET SYNCHRONOUS MACHINES

[1]H. MAHMOUDI , [2]A. LAGRIOUI
[1,2]Department of Electrical Engineering, xxx, YYY
Department of Electrical Engineering, Powers Electronics Laboratory
Mohammadia School of Engineering- BP 767 Agdal- Rabat -Morocco
E-mail: [1] mahmoudi.hassane@gmail.com, [2] lagrioui71@gmail.com

ABSTRACT

In this paper, a robust flux-weakening control scheme of PM synchronous machines is studied. Based on a novel current control concept, a speed/flux-weakening controller (SFWC) is proposed for the flux-weakening control of PMSM. Comprehensive analysis is conducted on the operations of PMSM controlled by SFWC in the flux-weakening region. Small-signal method is used to investigate the flux and torque controllability of SFWC. The current vector trajectories are modeled and illustrated in the rotor reference frame, with special attention to SPM motors. Efficiency-optimized design is performed on the selection of a newly introduced voltage constant. The Simulation results are provided to demonstrate the feasibility of the proposed control concept.

Keywords: *Speed/Flux-Weakening Controller (SFWC), permanent magnet synchronous machine (PMSM) Matlab/Simulink.*

1. INTRODUCTION

The permanent magnet synchronous machine (PMSM) has been increasingly applied in a wide variety of industrial applications. The reason comes from the advantages of PMSM: high power density and efficiency, high torque to inertia ratio, and high reliability. Recently, the continuous cost reduction of magnetic materials with high energy density and coactivity (e.g., samarium cobalt and neodymium-boron iron) makes the ac drives based on PMSM more attractive and competitive. In the high performance applications, the PMSM drives are ready to meet sophisticated requirements such as fast dynamic response, high power factor and wide operating speed range. This has opened up new possibilities for large-scale application of PMSM. Consequently, a continuous increase in the use of PMSM drives will surely be witnessed in the near future.

In this work, a robust flux-weakening control of PMSM is studied. With a novel current control strategy, i.e., adjusting the direct-axis voltage but fixing the applied quadrature-axis voltage of PMSM at a specific value, the demagnetizing stator current required for the flux-weakening operation can be automatically generated based on the inherent cross-coupling effects in PMSM between its direct-axis and quadrature-axis current in the synchronous reference frame. The proposed control scheme is able to achieve both flux-weakening control and speed regulation simultaneously by using only one speed/flux-weakening controller without the knowledge of accurate machine parameters and dc bus voltage of power inverter. Moreover, no saturation of current regulators occurs under any load conditions, resulting in control robustness in the flux-weakening region.

Therefore, our objective are to extend the operating speed range of the PMSM drive system and improve its control robustness and adaptability to variations of operating conditions as well as dynamic performance.

2. MODELING OF THE PMSM

The electrical and mechanical equations of the MSAP in the plane d-q can be written as follows [9]:

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$$u_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega\varphi_{sq}$$
$$u_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega\varphi_{sd} \quad (1)$$

With the field's equations as:

$$\varphi_{sd} = L_d i_{sd} + \varphi_f$$
$$\varphi_{sq} = L_q i_{sq} \quad (2)$$

We replace equation (2) into (1), the latter becomes:

$$u_{sd} = R_s i_{sd} + L_d \frac{di_{sd}}{dt} - \omega L_q i_{sq}$$
$$u_{sq} = R_s i_{sq} + L_q \frac{di_{sq}}{dt} + \omega L_d i_{sd} + \omega\varphi_f \quad (3)$$

The electromagnetic Torque it is given by:

$$T_e = \frac{3}{2} p.\left[(L_d - L_q).i_{sd} i_{sq} + \phi_f i_{sq} \right] \quad (4)$$

And the Mechanical Equation:

$$J\frac{d\Omega}{dt} + f.\Omega = T_e - T_L \quad (5)$$

Where:

R_s : Stator resistance

L_d, L_q : Stator d and q axis inductance

f : Viscous friction coefficient

J : Rotor moment of inertia

p : Number of pairs pole

ϕ_f : Permanent magnet flux

Ω : Motor speed

$\omega = p.\Omega$: Inverter frequency

i_{sd}, i_{sq} : d-q axis currents

u_{sd}, u_{sq} : d-q axis voltages

T_e : Electromagnetic Torque

T_L : Load Torque

3. OPERATION OF THE PERMANENT MAGNET SYNCHRONOUS MACHINE SUPPLIED BY A VOLTAGE INVERTER

In general, an inverter-fed PM synchronous machine, in an electrical ac drive system, can operate as either a motor or generator in both rotating directions, i.e., four-quadrant operation. On the other hand, constant torque can be delivered by a PM synchronous motor as long as the inverter output voltage doesn't reach its limit. Once the PM motor reaches its rated speed or base speed, the induced back-EMF in the stator windings approaches the maximum available terminal voltage. The torque would drop rapidly with speed increasing. To extend its operating speed range of PMSM, demagnetizing phase currents are generally applied to weaken the air-gap flux. This is known as flux-weakening control and thus the motor is operated in the flux-weakening region. As the speed continuously increases, the maximum output power may decrease due to the limited terminal voltages applied by the power inverter. With proper current control, instead, constant output power of PMSM can be achieved, referring to constant-power operation. Figure 1 shows a typical torque/power vs. speed characteristics curve of PMSM drive system. It can be seen that the large torque for starting and low-speed operation is required while the constant power over wide high-speed range preferred because it can significantly reduce the cost and size of the PMSM drive system.

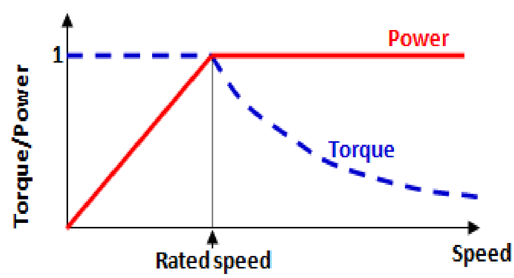

Figure1: Typical characteristics curve of torque/power vs speed of PMSM

4. RELATIONSHIP OF DQ-AXIS CURRENT IN THE ROTOR REFERENCE FRAME

In general, the dynamic equations of a PMSM in the rotor reference frame can be given in the matrix form as:

$$\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = \begin{bmatrix} R_s + sL_d & -\omega L_q \\ \omega L_d & R_s + sL_q \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\phi_f \end{bmatrix} \quad (6)$$

In steady state, the equations reduce to:

$$\begin{bmatrix} U_{sd} \\ U_{sq} \end{bmatrix} = \begin{bmatrix} R_s & -\omega L_q \\ \omega L_d & R_s \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\phi_f \end{bmatrix} \quad (7)$$

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Then, the electromagnetic torque of PMSM is expressed in terms of steady-state currents, i.e., I_{sd} and I_{sq}, as:

$$T_e = \frac{3}{2} p.\left[(L_d - L_q).I_{sd} I_{sq} + \phi_f I_{sq} \right] \quad (8)$$

When the direct current is oriented (i.e $I_{sd} = 0$) the expression of the torque becomes:

$$T_e = \frac{3}{2} p.\phi_f I_{sq} \quad (9)$$

From (7), we can find the relationship between the direct-axis current I_{sd} and quadrature-axis I_{sq} current of PMSM, which is partially expressed in:

$$I_{sq} = -\frac{\omega L_d}{R_s} I_{sd} + \frac{U_{sq} - \omega \phi_f}{R_s} \quad (10)$$

with $$\left| I_{sq} \right| \le \frac{U_{s\max}}{\omega L_q} \quad (11)$$

From (2) and (11) we obtain:

$$I_{sd} = \frac{1}{L_d} \sqrt{\left(\frac{U_{s\max}}{\omega} \right)^2 - \left(L_q I_{sq} \right)^2} - \frac{\phi_f}{L_d} \quad (12)$$

Equation (10) can be rewritten into:

$$I_{sq} = A_{dq} I_{sd} + B_{dq} \quad (13)$$

Where the coefficients are:

$$A_{dq} = -\frac{\omega L_d}{R_s} \quad \text{and} \quad B_{dq} = \frac{U_{sq} - \omega \phi_f}{R_s}$$

It is clearly shown in (13) that the linear relationship exists between the steady-state currents I_{sd} and I_{sq} at a specific speed, i.e., when the rotor speed, ω, is constant but nonzero. This is regarded as the cross-coupling effect in PM motors. When the speed changes, this relationship still keeps on but the coefficient A_{dq} i.e $-\frac{\omega L_d}{R_s}$, will be changed with the speed ω. It can be seen that the cross-coupling effect becomes stronger and stronger when the rotor speed goes higher, reflected by the increased coefficient. Therefore, in the flux-weakening region, the cross-coupling effect is dominant and should be dealt with properly for current regulation.

5. CONVENTIONAL CURRENT REGULATION IN FLUX-WEAKENING REGION

Conventionally, two current regulators are used to control the direct-axis and quadrature-axis current of PMSM respectively in the synchronous rotating reference frame. Thus both the magnitude and the angle of stator current vector can be controlled according to the vector control theory [3]. The type of current regulators is normally but not limited to proportional-integral (namely PI) controller. In a speed-controlled PMSM drive system, another speed regulator is required for the speed regulation, which is illustrated in Figure 2. The output of the speed regulator is the torque command based on the system mechanical dynamic equation specified by (5).

According to the given torque and operating speed, the direct-axis and quadrature axis current reference can be obtained from (8) and (12).

On the principle of vector control, it is expected that the torque and the stator flux of PM machines can be controlled independently. To PM motors, this is achievable through controlling the decoupled quadrature-axis and direct-axis current, i_{sq} and i_{sd}, respectively in the rotor reference frame. However, the current i_{sd} and i_{sq} can not be controlled independently due to the cross coupling effects, only by the voltage v_{sd} and v_{sq} which are the outputs of the two current regulators respectively, and expressed by:

$$\begin{cases} v_{sd} = k_{pd}\left(1 + \frac{1}{k_{id} s}\right) e_d \\ v_{sq} = k_{pq}\left(1 + \frac{1}{k_{iq} s}\right) e_q \end{cases} \quad (14)$$

with $$\begin{cases} e_d = i_{sdref} - i_{sd} \\ e_q = i_{sqref} - i_{sq} \end{cases}$$

where $k_{p_{d\,or\,q}}$ is the proportional gain and $k_{i_{d\,or\,q}}$ the integral constant of current PI-regulators.

Therefore, the dynamic performance of current response as well as torque response is strongly affected by the cross coupling effects in the high-speed flux-weakening region.

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By using feedforward compensation [3], the cross coupling might be cancelled in the steady state as shown in Figure 2. Thus the voltage commands are determined by the outputs of current regulators and the decoupling feedforward compensation, v_{sd-fc} - v_{sq-fc}:

$$\begin{cases} v_{sd-fc} = -\omega L_q i_{sq} \\ v_{sq-fc} = \omega L_d i_{sd} + \omega \phi_f \end{cases} \tag{15}$$

Hence, the direct-axis and quadrature-axis current loops can be linearized by the above decoupling method.

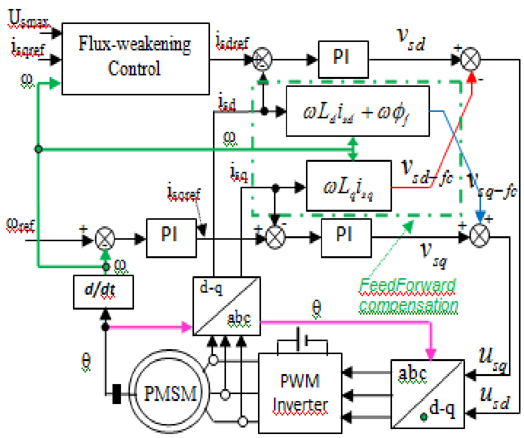

Figure 2. Bloc diagram of speed regulated PMSM drive system with flux weakening control

6. DESIGN OF SPEED/FLUX-WEAKENING CONTROLLER

Define a positive voltage constant, U_{FC}, which is less than the maximum phase voltage $U_{s\max}$, i.e, 0<U_{FC} <$U_{s\max}$ Let the quadrature-axis voltage of PMSM equal the voltage constant U_{FC} .

Considering (13), we get that all the following coefficients are constant at a given speed:

$$A_{dq} = -\frac{\omega L_d}{R_s} \text{ et } B_{dq} = \frac{U_{FC} - \omega\phi_f}{R_s}$$

As a result, the linear relationship between the steady-state currents I_{sq} and I_{sd} at the speed ω, as shown in (13), suggests a control strategy that the quadrature-axis current, or torque, can be controlled by means of controlling the direct-axis current. This, actually, utilizes the inherent cross-coupling effects inside the PM motor instead of cancelling them as in the system shown in Figure2. By fixing the quadrature-axis voltage u_{sq}, the quadrature-axis current regulator can be eliminated. Therefore, only one direct-axis current regulator is required for the torque and flux control in the flux-weakening region.

It should be noticed that this I_{sd} –based torque control method may work in the constant torque region below the base speed but it would not be current-efficient, resulting in excessive copper losses.

Integrating speed regulation, a flux-weakening control scheme is illustrated in Figure3 which includes a speed/flux-weakening controller, namely SFWC. A speed-regulated PMSM drive system including the SFWC is also shown in Figure 4. The speed/flux weakening controller is designed with but not limited to a PI-regulator. The input of SFWC is speed error, $e_\omega = \omega_{ref} - \omega$, and the output is the direct-axis current reference i_{sdref}. The generated direct-axis current reference is negative, i.e., $i_{sdref} \prec 0$, which consists of two components: one is the required demagnetizing current; and the other is the torque component referring to the demanded torque by the speed regulation through the cross coupling effect. It implies that the demagnetizing current can be automatically generated which is adaptive to the rotor speed and operating conditions such as load level or dc bus voltage. With applying the fixed quadrature-axis voltage u_{sq}, the direct-axis current is controlled by adjusting the direct-axis voltage u_{sd} through the direct-axis current regulator.

Therefore, only two PI-regulators are used for both flux and speed (or torque) control while three PI-regulators used as shown in Figure2.

The transfer function of the speed/flux-weakening controller can be expressed as:

$$i_{sdref} = -k_{p\omega}(1 + \frac{1}{k_{i\omega} s})e_\omega \tag{16}$$

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

$k_{p\omega}$ and $k_{i\omega}$ are the proportional gain and the integral constant respectively.

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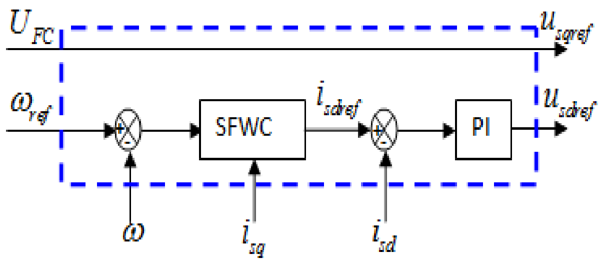

Figure3. Block diagram of flux-weakening control with SFWC

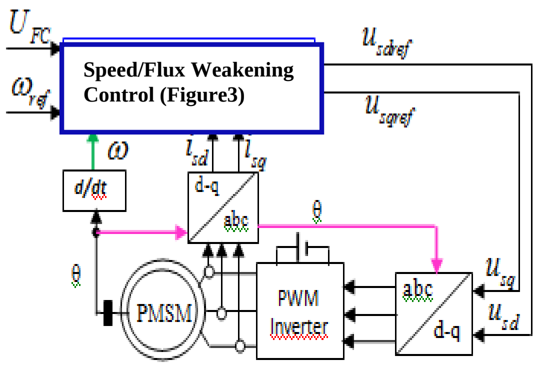

Figure4: Block diagram of speed-regulated PMSM drive system with SFWC in the flux-weakening region

7. SIMULATION AND EXPERIMENTAL RESULTS

Computer simulations have been conducted to verify the control performance of the speed/flux-weakening controller. Matlab/Simulink® with SimPowerSystems Blockset is used as simulation platform. A Simulink model of PMSM drive system including SFWC is built and shown in Appendix A. The machine parameters of the simulated PMSP motor and drive system are given in Table I. And the simulation parameters of Simulink are given in Table II.

7.1 PMSM parameter's

TABLE I. PMSP PARAMETRE'S

paramètre	Valeur
Nominal Voltage	300 v
Maximum speed	3000 tr/s à 150 Hz
Nominal torque	14.2 N.m
Stator resistance R_s	0.4578 Ω
Number of pair poles p	4
L_d	3.34 mH
L_q	3.58 mH
Moment of inertia J	0.001469 kg.m2
Coefficient of friction viscous f	0.0003035 Nm.sec/Rad
Flux of linuqage ϕ_f	0.171 wb

TABLE II. SIMULATION PARAMETRES OF SIMULINK

Solver Type	Ode23t
Max step size	1e-6
Min step size	auto
Initial step size	1e-6
Relative tolerance	1e-4
Absolute tolerance	auto

7.2 Simulation results

Figure 5 to Figure 9 show the simulation results in which the motor is first accelerated from 0 to 200 rpm and then stays for 0.26 second and finally decelerates down to 0 rpm without load. The rate of acceleration is not the same as that of deceleration.

The onset of flux-weakening operation is set at speed 25 rpm. The voltage constant is set with $U_{FC} = 300$, for the speed/flux-weakening controller.
The dc bus voltage is 300V consistently. We can observe the automatically generated demagnetizing current i_{sd} by SFWC and its good performance of speed regulation within the wide speed range in the flux-weakening region.
It should be noticeable that current transients exist during the transition from normal to flux-weakening operation of the PMSM motor and vice versa. A straightforward method is used for initiating the transition, by which the speed/flux-weakening controller is activated once the motor speed reaches the preset onset speed during acceleration and inversely deactivated during deceleration. A smooth transition can be made by advanced control algorithms.

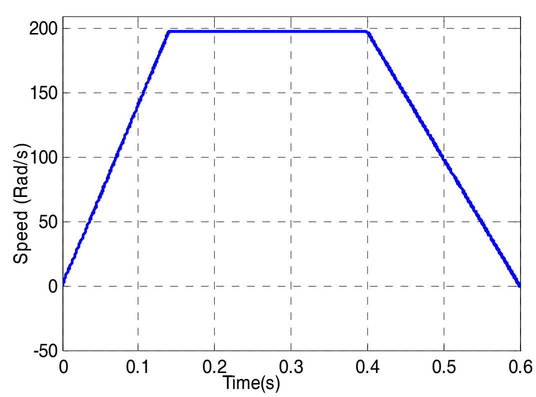

Figure5: Performance of the PMSM with speed ramping up and down.

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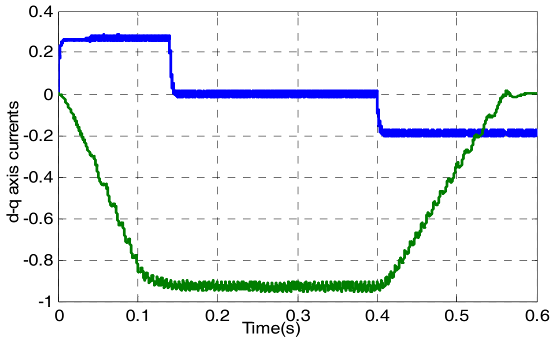

Figure6: Performance of the PMSM with speed ramping up and down.

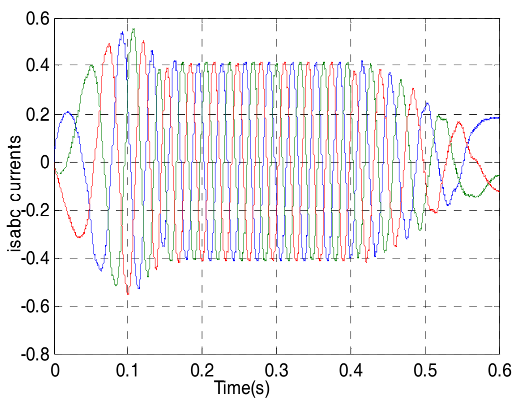

Figure7: Three phase currents stator

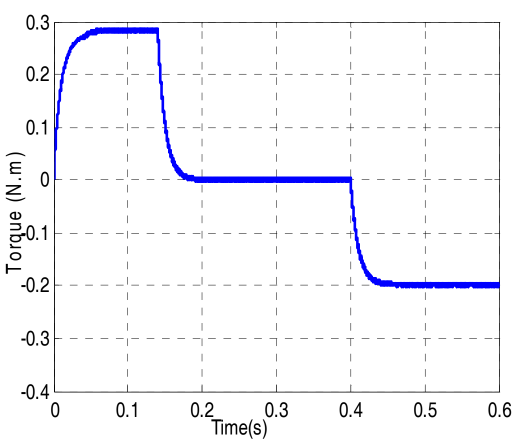

Figure8: Performance of the PMSM with speed ramping up and down.

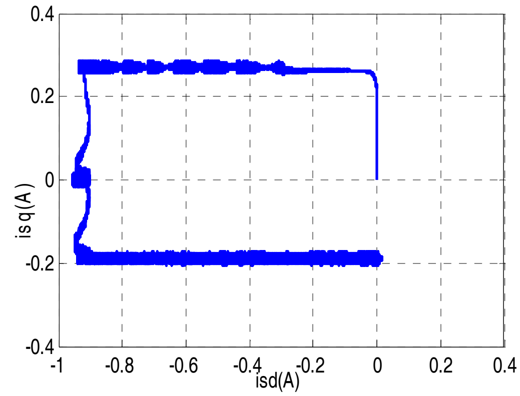

Figure 9: is-d-q axis currents trajectory.

Figure 10 to Figure14 shows the robustness of the simulated drive system with respect to disturbances from load and dc bus voltage. In the simulation, the PMSP motor is accelerated from 0 to 200 rpm and maintains at this speed after the time t =0.2 s. The dc bus voltage is initially 300V and increased to 310V with a ramp from t =0.2 to 0.3 s, and then decreases to 270V gradually where the dc bus voltage stays thereafter. The load torque is initially 0.2 N.m and stepped to 0 N.m at time t =0.2 s. We can observe that the speed error is much less than 1.2% in per unit at 200 rpm, which refers to 8.5%, in both steady state and transient in the flux-weakening region. It indicates that the speed regulation in the flux-weakening region functions very well with either dc bus or load disturbance. The proposed speed/flux-weakening controller is therefore proven to be adaptive to variations of dc bus voltage and load level.

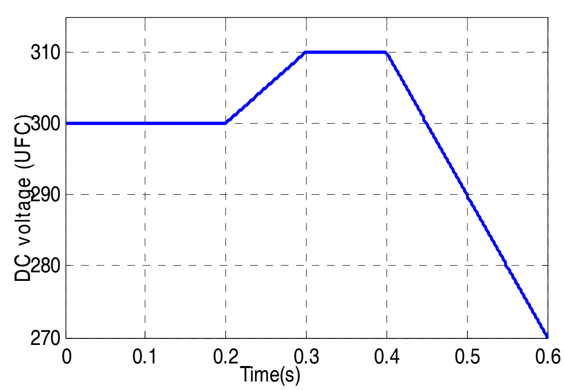

Figure10: Simulation results of PMSM drive system with disturbances of dc bus voltage and load.

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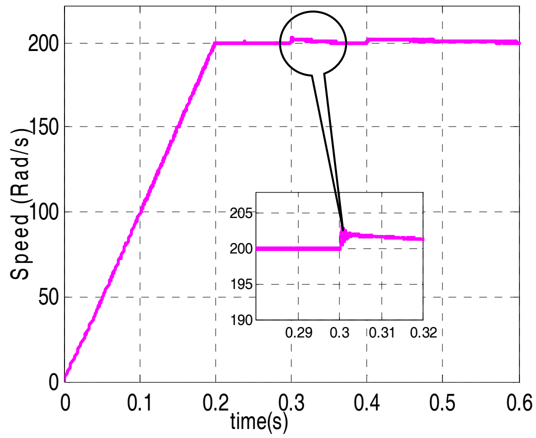

Figure 11: Simulation results of PMSM drive system with disturbances of dc bus voltage and load.

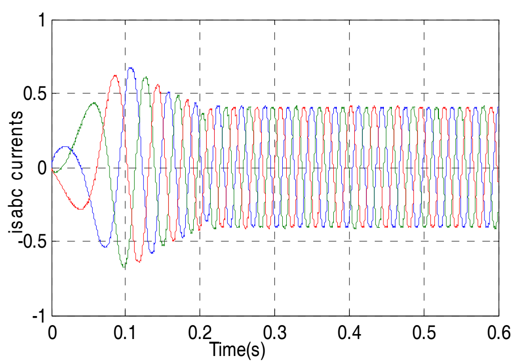

Figure12: Performance of the PMSM with speed ramping up and down.

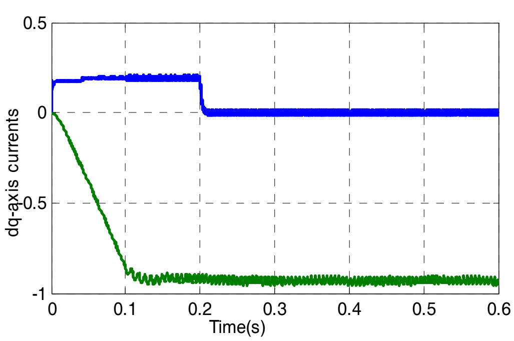

Figure13: Performance of the PMSM with speed ramping up and down.

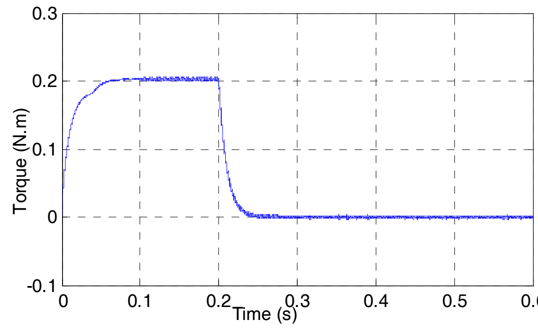

Figure14: Performance of the PMSM with speed ramping up and down.

8. CONCLUSION

In this paper, a robust flux-weakening control scheme has been studied, which incorporates the speed regulation of the PMSM drive system. It utilizes none of accurate machine models but the cross-coupling effects inherent to PMSM, and thus it is robust and insensitive to the variation of machine parameters and operating conditions. This flux-weakening control scheme is adaptive in the sense of automatic generation of the desired demagnetizing current considering both current and voltage constraints over full speed range.

In contrast to employing the conventional two-loop current regulation, the PMSM drive with the developed speed/flux-weakening controller is able to achieve both flux-weakening and speed control simultaneously, as well as preventing from saturation of current regulators in the flux-weakening region. This feature will bring the advantage of reduced computation/execution time to cost-effective drive systems.

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AUTHOR PROFILES:

Dr. Hassane MAHMOUDI was born in Meknes city, Morocco, on January 4, 1959. He received the B.S degree in electrical engineering from Mohammadia School's of engineers, Rabat, Morocco, in 1982, and the Ph.D. degree in power electronic from Montefiore Institute of electrical engineering, Luik, Belgium, in 1990. He was an Assistant Professor of physics, at the faculty of sciences, Meknes, Morocco, from 1982 to 1990. Since 1992, he has been a professor at the Mohammadia School's of engineers, Rabat, Morocco, and he was the head of Electric Engineering Department during four years (1999, 2000, 2006 and 2007). His research interests include static converters, electrical motor drives, active power filters and the compatibility electromagnetic.

Ahmed LAGRIOUI was born in taounate city –Morocco, on 1971. He received the aggregation degree in electrical engineering from the ENSET School, in 2003. He received the DESA degree in industrial electronics from the Mohammadia school's of engineers. His research interests include static converters, electrical motor drives and power electronics