Nonlinearities's Recoupment of Interior Permanent Magnet Synchronous Motor Drives

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Abstract *Variable Speed Control schemes of electric drives with Permanent Magnet Synchronous Motors contain microcontrollers of high quality in order to provide implementation of complex control algorithms to ensure high performance for speed and torque control. Since in practical industrial applications, this is not always demanded, make sense the construction of simpler schemes that adopt simpler algorithms and need no costly microcontroller. In this paper we have developed a simplified scheme for speed and torque control of PMSM drive having only one control loop (the traditional scheme has 2 loops) and only one PI controller (the traditional scheme has 3 PI controllers). Because of the electric drive of PMSM has an emphatic presence of nonlinearities, our expectations related with performance are not too high. Our contribution consist in modifying the PI controller with nonlinearities added purposely in order to obtain technical improvements for speed response. Our scheme is developed and tested at MATLAB/Simulink and confirm that the nonlinearities are very good tools for nonlinearity 's recoupment of PMSM drives.*

Keywords— *nonlinear PI controller, PMSM, simplified scheme for VSC drives.*

I. Introduction

The electric drives with PMSM are commonly used for applications with high demands related to control performance of speed and torque [1]. Among different methods developed and used from researchers, the most discussed and matured is Vector Control Method or Field Oriented Control, which is became an industrial standard already. That approach use a scheme with two control loops and three PI controllers (one for speed and two for currents of d,q axes). Tuning process of three PI controllers is considered a really challenge for the most of designers, especially the PI controllers of currents loop. Moreover, the algorithm execution need a high performance microprocessor that result a costly drive. In special cases of industrial applications the goal is to realize an electric drive for speed and torque control of PMSM using an existing microprocessor of our laboratory. Using this microprocessor has the utility to use a known device, and the duty will be reached faster. The technology of electronic devices is faced with an explosive development resulting in a faster moral consume of electronic devices. So is duty of engineers to use better the existing devices for a higher productivity. The aim of this paper is to propose a simplified scheme for speed and torque control of PMSM. Because of the PMSM has a strongly nonlinear character, it is not too easy to design a control scheme with a single conventional PID controller. So, we have to modify that PID controller in order to meet the control quality. What we have to propose is adding nonlinearities in control loop consciously for nonlinearity's recoupment of PMSM drive.

II. Model of IPMSM

In proposed scheme we have used the wide world known and accepted model of IPMSM on d, q frame [2], [3]. The equations that describe the electrical dynamics are as below:

$$v_d = R_s \cdot i_d + \frac{d\Psi_d}{dt} - \omega_r \cdot \Psi_q = R_s \cdot i_d + L_d \frac{di_d}{dt} - \omega_r \cdot L_q i_q$$

$$v_q = R_s \cdot i_q + \frac{d\Psi_q}{dt} + \omega_r \cdot \Psi_d = \qquad (1)$$

$$= R_s \cdot i_q + L_q \frac{di_q}{dt} + \omega_r \cdot L_d \cdot i_d + \omega_r \cdot \Psi_{PM}$$

The corresponding electromagnetic torque production is:

$$T_e = \frac{3}{2} p \cdot i_q (\Psi_{PM} - (L_q - L_d) \cdot i_d) \qquad (2)$$

The associated electromechanical equations are as follows:

$$J \frac{d\omega_r}{dt} + B\omega_r = T_e - T_L$$
$$\frac{d\theta_r}{dt} = \omega_r \qquad (2')$$

Based on these equations, we have built the diagram block of the IPMSM in MATLAB/Simulink for a motor with parameters as below in Table 1:

TABLE I

PMSM PARAMETERS [4]		
Parameters	**Symbol**	**Values[Unit]**
Nominal Power	P_n	1000[W]
Nominal Speed	ω_n	1500[rev/min]
Stator Resistance	R_s	1.4[Ω]
Inductance in d-axis	L_d	0.0056[H]
Inductance in q-axis	L_q	0.009[H]
Magnetic Flux	Ψ_{PM}	0.1546[Wb]
Pole Number	p	6
Inertia	J	0.006[kgm^2]
Friction coefficient	B	0.01[Nms]

The detailed presentation of IPMSM in MATLAB/Simulink is shown in Figure 1.

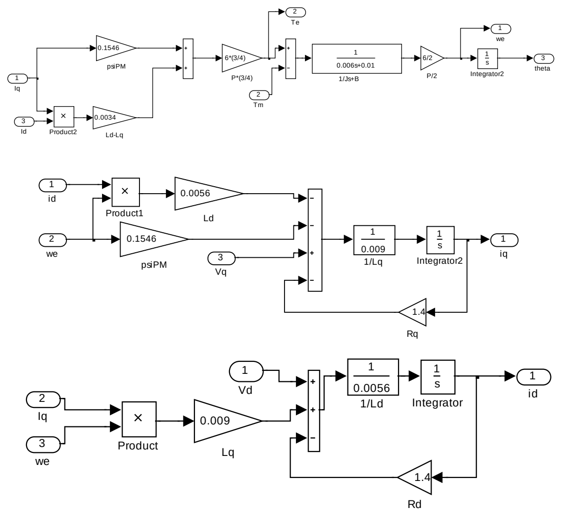

Fig. 1. Block diagrams of IPMS in MATLAB/Simulink. The upper block shows the mechanical dynamics, the lower blocks show the electrical dynamics.

A. Design of linear PI speed controller

In order to enhance the performance of linear PID controllers, many approaches have been developed to improve the adaptability and robustness by adopting the self-tuning method, general predictive control, fuzzy logic and neural networks strategy, and other methods [5–13].It is well known that (linear) PI controllers, if suitably tuned, provide satisfactory solutions to many practical applications without requiring a detailed description of the system dynamics. In the presence of strong nonlinear effects, however, their performance is below par, and it is necessary to “re tune” the controller appealing to gain scheduling or adaptive procedures [14]. In most of practical cases our knowledge and description of nonlinearities present in system is inaccurate, so the design of tuning procedure ensue complicated. The design of current and speed controllers is usually based on linear control system techniques such as the Bode plot or the root locus or by using standard optimum functions such as the symmetric optimum. The design of the speed controller is important from the point of view of imparting desired transient and steady-state characteristics to the speed-controlled PMSM drive system.

In a PID controller, integral effect can reduce system steady-state error and improve its steady performances. But, if too large, it will lead to integral saturation and big overshoot .As for differential effect, it has ability to obtain the trend of signal error sensitively, which means differential has a certain degree of predictability. However, differential can only act in dynamic process, in that it is expressed as the ratio of error incremental to time incremental. Furthermore, it is very sensitive to noise, which can cause system instability easily [15].

A proportional plus integral controller is sufficient for many industrial applications. Selection of the gain and time constants for such a controller using the symmetric optimum principle is straightforward if, the d-axis stator current is forced to be zero. In the presence of the d-axis stator current, the d- and q-current channels are cross-coupled and the model is nonlinear due to the torque term. With the assumption that ids =0, the system becomes linear and resembles a separately excited dc motor with constant excitation. From then on, the block diagram derivation, current loop approximation, speed loop approximation, and the derivation speed controller using symmetric optimum becomes identical to that of dc and vector-controlled induction motor drive speed controller design procedures [16].

Since the dynamics in electric drives are generally fast or very fast, the PI controllers are sufficient to control speed or stator’s currents on d,q frame. After verification of stable operation, for a better performance (our expectation is to be not quite enjoyable) the coefficients of PI controller are gained in three different manners:

1) by using standard optimum functions such as the symmetric optimum.
2) by using an optimization procedure in MATLAB with SISO Design Tool.
3) By using Lennart Harnefors method

This method is based on IPMSM’s parameters and on inverter’s parameter to determine the PI controller coefficients [17].

The design requirements that speed PI controller has to fulfill are as below:
a) overshoot less than 10%.
b) stabilization time less than 30ms.
c) steady state error less than 0.01%
in presence of step load disturbance.

Table II shows the results taken for speed PI controller parameters calculated by methods mentioned early.

TABLE III

SPEED PI CONTROLLER PARAMETERS		
Parameters	k_p	k_i
Symmetric Optimum	0.749,	48.46
Optimization in MATLAB	0.5725,	118.3
Lennart Harnefors method	0.75,	50.2

The results of these methods are different. More, these coefficients are synthesized for linearized model of IPMSM using its transfer function for speed. So it is strongly needed to verify the speed response for each of them in the whole scheme build in MATLAB/Simulink, shown in Figure 2.

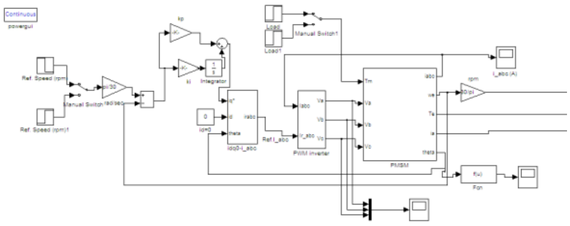

Fig. 2. Block diagram of system controlled with PI speed controller in MATLAB/Simulink.

Results of speed responses are compared to choose the better set of coefficients that meet the design requirements. These results are shown in Figure 3.

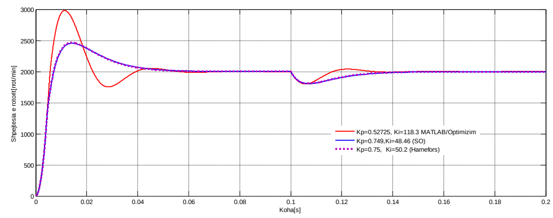

Fig. 3. Speed responses for system controlled with PI speed controllers synthesized by different manners.

From graphics of Figure 3, is clearly seen that the difference is for transient response. The first and second criteria for quality of regulation are fitted better (but not passably) by PI controllers synthesized by Symmetric Optimum method and by Lennart Harnefors method.

B. Our proposal

The step response figure out clearly that our nonlinear system (IPMSM drive) can't be controlled conform quality criteria of regulation using linear PI controllers synthesized for linear model. So, we propose to purposely add in speed control loop some nonlinearities in order to achieve better dynamic performance for speed response of our system.

III. DESIGN OF NONLINEAR CONTROL

In typical control engineering problems nonlinearity may occur in the dynamics of the plant to be controlled or in the components used to implement the control. Alternatively, we may have intentional nonlinearities which have been purposely designed into the system to improve the system specifications, either for technical or economic reasons.

Identifying the precise form of a nonlinearity may not be easy and like all modeling exercises the golden rule is to be aware of the approximations in a nonlinear model and the conditions for its validity.

Linear Control Theory can't be useful for nonlinear systems. Refer to the most successful researchers on this field, we may say that there are not analytical methods to predict the behavior of such systems. Different methods are proposed and developed for control of nonlinear systems like Phase Plane Method, The Describing Function Method, etc., but still they have their limitations in application's and mode of operation's point of view. So, an alternative way to overpass the difficulties of analytical analyses of nonlinear systems is simulation with computer. The enormous importance that has the studying through simulation must be undivided and combined with theoretical analysis of systems. This is the methodology used in this paper to figure out the results. To be more concrete, we have applied a combination of Describing Function Method with simulations on MATLAB/Simulink.

A. Modification of speed PI Controller

Linear speed PI controller designed early seemed to be insufficient to control the behavior of IPMSM drive conform requirements of control quality needed. This insufficiency is due to emphatic presence of nonlinearity in our system.

In this paper, instead of developing highly complex and nonlinear compensation schemes, we will adopt the simplest iterative learning law and demonstrate the desirable property of unknown nonlinearities compensation.

An available idea is that nonlinearity may be recompensed making a modification on speed control loop, in other words, adding another nonlinearity or a combination of two nonlinearities for a better performance in dynamic response of speed and torque. In this paper, we have used two types of nonlinearities: "dead zone" (DZ) and "saturation" (S). These nonlinearities are combined as below:

- DZ in parallel with S
- DZ in cascade with S
- DZ only

The combined nonlinearities are connected in cascade with conventional PI speed controller that we have synthesized earlier. So, the scheme for speed control of IPMSM with linear PI controller, we have developed in MATLAB/Simulink, will be modified in three different versions, as shown in Figures 4,5,6.

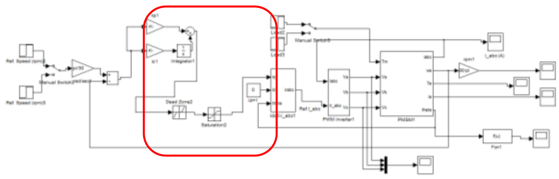

Fig. 4. Scheme of speed control of IPMSM with modified PI controller adding in cascade the combination DZ in cascade with S.

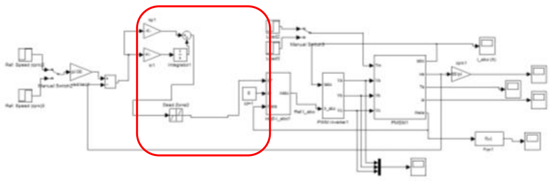

Fig. 5. Scheme of speed control of IPMSM with modified PI controller adding in cascade the nonlinearity DZ .

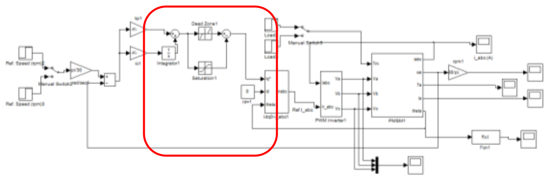

Fig. 6. Scheme of speed control of IPMSM with modified PI controller adding in cascade the combination DZ in parallel with S.

B. Stability and Limit Cycles using the DF

The problem of determining precisely the stability of an autonomous nonlinear feedback system, even one simply containing one linear dynamic element and one nonlinearity, has not been solved, even though it has exercised the minds of mathematicians and engineers for years. The DF provides an approximate method for answering the problem [18].

Our initial investigations are concerned with the stability of the autonomous system, that is r(t) = 0, the linear dynamic blocks of IPMSM drive are in series and can be represented by the single transfer function G(s). Further the position of the single static nonlinearity although assumed in the forward path could equally well be in the feedback path.

An early contribution to the problem was a conjecture by Aizermann. He conjectured that if a symmetrical odd nonlinearity was confined within a sector defined by straight lines of slope k_1 and k_2 then any nonlinear system with a nonlinearity lying entirely within the sector would be stable or possess a limit cycle provided the linear system was stable for gains between k_1 and k_2. Thus, since use of the DF provides an approximate method for the determination of limit cycles, it also provides an approximate stability test for our simple feedback loop. To study the possibility of limit cycles in the autonomous closed loop system of Figure 7, the nonlinearity n(x) is replaced by its DF N(a).

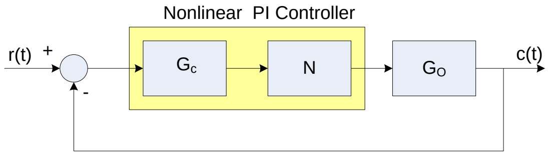

Fig. 7. Scheme of the autonomous closed loop system.

Thus, the open loop gain to a sinusoid is N(a)G(jω) and a limit cycle will exist if:

$$1+ N(a)G(j\omega)=0 \text{ , or } \quad N(a)G(j\omega)= -1 \qquad (3)$$

where

$$G(j\omega) = G_C(j\omega)G_O(j\omega) .$$

This condition means that the first harmonic is balanced around the closed loop assuming its passage through the nonlinearity is accurately described by N(a). Since G(jω) is a complex function of w and N(a) may be a complex function of a, a solution to (3) will yield both the frequency ω and amplitude a of an assumed sinusoidal limit cycle. Typically the functions G(jω) and N(a) are plotted separately on Bode, Nyquist, or Nichols diagrams. Alternatively, stability criteria such as the Hurwitz-Routh or root locus plots may be used for the characteristic equation (4)

$$1+ N(a)G(s)=0 \qquad (4)$$

although here it should be remembered that the equation is appropriate only for s ≈ jω.

Figure 8 and 9, illustrates the procedure on a Nyquist diagram, where the G(jω) and C(a)=-1/N(a) loci are plotted and shown intersecting at P for $a = a_0$ and $\omega = \omega_0$. The DF method therefore indicates that the system has a limit cycle with the input sinusoid to the nonlinearity, x, equal to $a_0 \sin(\omega_0 t + z)$, where z depends on the initial conditions and time origin. In practice the limit cycle will not be sinusoidal and a_0 is an approximation for the amplitude of the fundamental component of the limit cycle. Thus, to estimate the accuracy of the DF prediction for a limit cycle, we should measure the amplitude of the fundamental, not the peak amplitude of the waveform as is often done for convenience.

When the G(jω) and C(a) loci do not intersect, the DF method predicts that no limit cycle will exist if the Nyquist stability criterion is satisfied for G(jω) with respect to any point on the C(a) locus. Obviously, if the nonlinearity has unit gain for small inputs, the point (- 1, j0) will lie on C(a) and it may then be used as the critical point, analogous to the situation for a linear system.

When the analysis indicates the system is stable, its relative stability may be indicated by evaluating its gain and phase margin. These can be found for every amplitude a on the C(a) locus, so it is usually appropriate to use the minimum values.

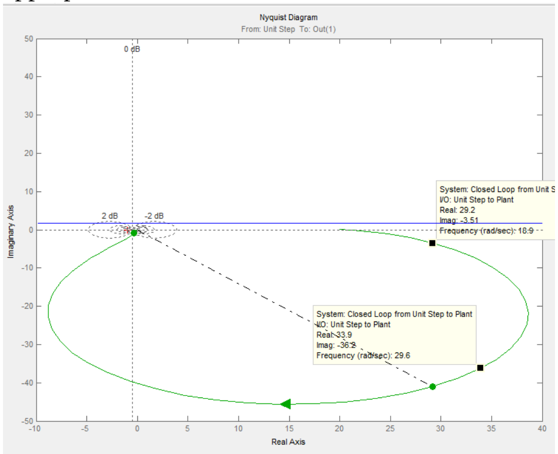

Fig. 8. Procedure on a Nyquist diagram, where the G(jω) (in green) and C(a) =- 1/N(a) loci (in blue) for nonlinearity DZ in cascade with S.

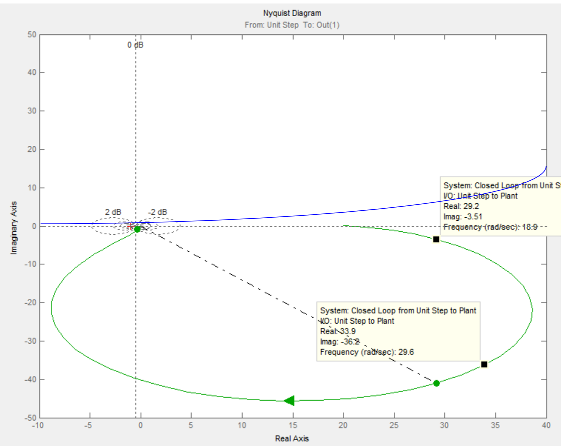

Fig. 9. Procedure on a Nyquist diagram, where the G(jw) (in green) and C(a) =- 1/N(a) loci (in blue) for nonlinearity DZ .

IV. SIMULATION AND RESULTS

Graphical results of Figure 8 and 9, show that nonlinearities added purposely on the speed control loop for IPMSM drive do not corrupt the stability of system since the G(jω) and C(a) loci do not intersect in both cases. That means we may go on take care of control quality and overall performance in dynamic and steady state operation. The simulation schemes shown on Figure 4,5,6, are tested in different scenarios related to speed reference and torque disturbance for a better evaluation of performance and for a deep knowledge of limitations of designed nonlinear PI speed controller. The Figures 10,11 and 12 show results of simulation for the first scenario:

A. *Reference speed :1500rev/min to 150 rev/min; reference Torque: 4Nm to -4Nm*

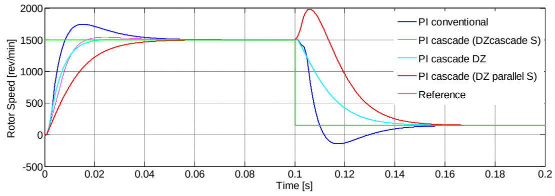

Fig. 10. Comparison of Speed control of IPMSM drive for command speed changing from nominal speed 1500 rev/min to very low speed (10% of nominal speed ,150 rev/min) in presence of step load disturbance .

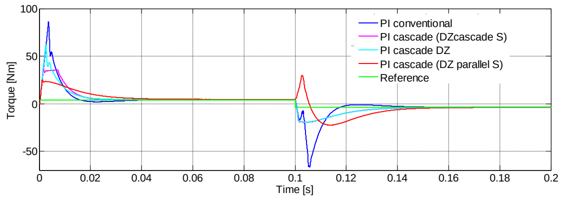

Fig. 11. Comparison of Torque control of IPMSM drive for command Torque changing from 4Nm to-4Nm

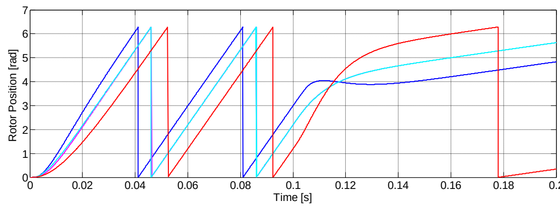

Fig. 12. Comparison of Rotor position control of IPMSM drive for command Torque changing from 4Nm to -4Nm and command speed changing from 1500rev/min to 150rev/min.

The behaviour of system in presence of nonlinearities is quite different during dynamic operation, but in each case better than conventional PI controller. The overshoot is approximately zero while time of stabilization is equal in some cases or less in case of PI in cascade with DZ, which realize the best performance compared with other combinations.

Since our solution for nonlinear elements used to modify the conventional PI controller is not an analytical one, need to verify the behaviour of our system in other scenarios.

B. *Reference speed :1500rev/min to -1500 rev/min; reference Torque: 4Nm*

The stable operation with prompt changes in speed reference signal , from motor to reverse rotation, is very important for many kind of industrial applications with IPMSM. This scenario tend to test the drive behaviour in that case.

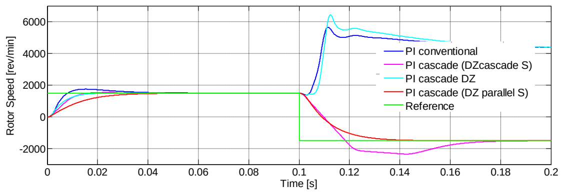

Fig. 13. Comparison of Speed control of IPMSM drive for command speed changing from nominal speed 1500 rev/min to -1500 rev/min) in presence of constant load.

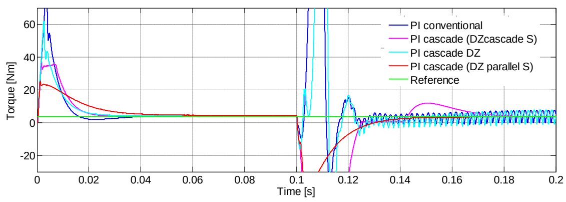

Fig. 14. Comparison of Torque control of IPMSM drive for constant command Torque 4 Nm.

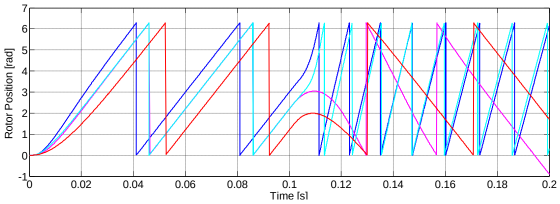

Fig. 15. Comparison of Rotor position control of IPMSM drive for constant command Torque 4Nm and command speed changing from 1500rev/min to -1500 rev/min.

Refer to Figures 13,14,15, is evident that nonlinearities effect the system in different manners. In each case the system is stable but nonlinearity DZ and conventional PI cause a torque ripple that can't be ignored for negative nominal speed. More, for negative nominal speed the control speed is not achieved in all cases. The combined nonlinearities DZ parallel S in cascade with PI controller have the best behaviour in dynamic and steady state operation compared to other schemes.

To complete our discussion, let see the results from simulation of this scenario:

C. Reference speed: 2500rev/min to 0 rev/min; reference Torque: 4Nm

This scenario tend to test the IPMSM drive operation with high speed under constant torque load. By simulations are compared results for speed, torque and position (rotor angle) in IPMSM drive controlled with conventional PI and different kind of nonlinear PI controllers.

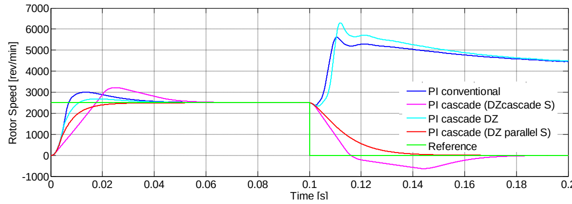

Fig. 16. Comparison of Speed control of IPMSM drive for command speed changing from speed 2500 rev/min to 0 rev/min) in presence of constant load.

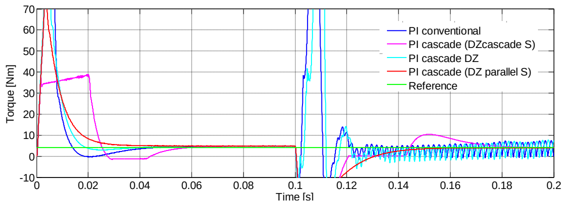

Fig. 17. Comparison of Torque control of IPMSM drive for constant command Torque 4Nm .

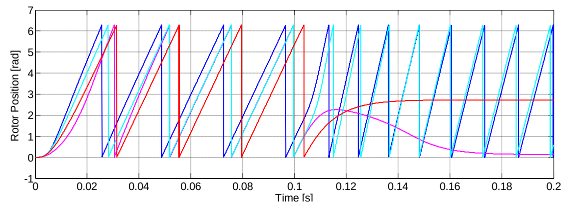

Fig. 18. Comparison of Rotor position control of IPMSM drive for constant command Torque 4Nm and command speed changing from 2500rev/min to 0 rev/min.

Results of last scenario, shown on Figures 16, 17, 18, show that compared to nominal regime where all combinations of nonlinearities have a good effect on dynamic response, in high speeds, the behaviour change and only one of them give a good effect. On the other side, the behaviour of system on zero speed and negative speeds is the same. During these scenarios only one combination PI in cascade with DZ in parallel with S guarantee a speed and torque control with good quality.

IV. CONCLUSIONS

Through a combined technique involving simulation and analytical analyze by method of Describing Function, in this paper are shown results concerning with effects of added by design nonlinearities because of insufficiency of linear PI controller to compensate totally the strongly presence of nonlinearity in an IPMSM drive. We have simulated in MATLAB/Simulink a simplified scheme based on FOC, and we tested some extreme mode of operation like: zero speed operation, very low speed operation (10% of nominal speed), high speed (166% of nominal speed), nominal negative speed. These tests are made under step load disturbance and under constant torque on the motor shaft.

By these graphics is confirmed that behaviors of nonlinear feedback systems are unique, aspects which make such systems extremely interesting. However, it has meant that no general analytical method is available for predicting their behavior. Our discussion is restricted in their applicability or, put alternatively, the situations which they can address. More, the importance of simulation studies for investigating nonlinear systems in association with analytical methods cannot be underestimated. Care has to be taken in simulating nonlinear systems particularly those with linear segmented characteristics because of the discontinuities.

The usefulness of this paper comes from possibility that provide a solution in cases of electric drives in order to adopt them in industrial applications with no added costs. The results achieved give good example how to use effectively the nonlinearities or their combination for having a better technical and economically performance in electric drives with IPMSM.

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