Observer-based Linear Control of Synchronous Machine with Damper and Excitation Winding

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Abstract: This paper proposes a novel control system for synchronous machine rotor speed control. Based on deterministic observer and cascaded loops, a linear control system is obtained. Stability proof of the observer and linear analysis of the control system is given. Simulation studies of the machine starting, speed reversal and step loading are presented. A Comparison Analysis with the nonlinear control method, is also presented.

Keywords: synchronous machine; observer; linear control; nonlinear control

1   Introduction

The scope of this work is synchronous machine operation as an AC drive system. Synchronous machine (SM) is considered in its full complexity: saliency, excitation and damper windings. There is need for an AC drive system with this kind of SM when variable speed operation is requested. Whenever the frequency converter is connected with the SM, its control has to be designed. This occurs in hydropower, wind power, industrial applications (fan, compressor, conveyor belt) and in propulsion systems. By changing amplitude, frequency and vector position of the supplied voltage, rotor speed (or electromagnetic torque) and magnetic flux are controlled. Obtaining adequate control system for such SM is very challenging and there are not many research studies either with linear or nonlinear control systems.

In classical linear control system [1], dynamics of the damper winding currents are neglected. Calculation of magnetic fluxes has not stability proof. Consequently, it is possible for the drive system to become unstable. Due to this, classical SM drive system needs three control variables to obtain the control of two outputs. The control variables are stator voltage components u_d and u_q, and excitation winding voltage u_f. The output (controlled) variables are only two: rotor speed or

electromagnetic torque, and magnetic flux. Except form that, decoupling between rotor speed and magnetic flux control is hard to obtain by the classical system [2]. Due to this, instead of rotor flux orientation, stator flux orientation control system is obtained [3-7]. However, [3-7] lack in stability proof of the controller. Whether DTC [8] or vector control principles are used, three control inputs are always in use and damper winding current dynamics are always neglected. Regarding nonlinear control of the SM, there are few studies [9-10] in which mathematically proved control law is obtained without neglecting complexities of the SM dynamical system. In [9-10], again three control variables have to be used. In [11-12], two control variables are used, but obtained control law needs to be predictive. Except from that, the control law strongly depends on load torque. Although a load torque estimation algorithm has been given [11-12], it could be seen that load torque estimation relay upon calculation of the electromagnetic torque. Literature [11-12] also use feedback linearization method. Taking all of that into consideration, there might be significant loss of precision due to parameter variation in the case [11-12] is used in praxis.

Except from motor control, literature review of the control system principles used in various industrial applications is also done. State space representation of the controlled plant is the starting point of the control system design even when the plant is nonlinear [13]. To obtain the precise control using linear control techniques, usually cascaded control system with inner and outer control loops is designed [14]. If the plant model is well known, some advanced control methods such as modified shared circuit model (MSCM) [15] or already known internal model control (IMC) could be used to obtain the controller parameters. Literature also gives vast number of artificial intelligence methods such as neural networks used in control system applications [16] [17]. Stability of the robot control applications is proved by the Lyapunov function [18]. If a dynamical system of the controlled plant is not known, various data driven algorithms have been developed. In [19], data driven CFDL-PDTSFA algorithm is used to obtain the tower crane control.

In this work, a novel linear control method for the SM control is presented. Because SM model and its identification is known, starting point of the control design is state space representation. To obtain the complete state vector, an observer for the damper winding has to be designed. Stability of the observer is proved by Lyapunov function. Linear control principles are used and cascaded control system is designed. Design of the inner control loops use IMC principle. In comparison with classical linear control, some improvements have been made. At first, deterministic observer for the damper winding states have been given and used in obtaining decoupled control. Finally, a control system needs only two control inputs. Regarding nonlinear control systems, novel linear control does not need load torque estimation and generally is less dependent on SM parameter variation. In addition, novel linear control does not need any a priori knowledge of reference values.

After the introduction with literature review, a novel deterministic observer is given in Chapter 2. Dynamical system and its stability proven observer are presented there. Using this observer, linear control system is obtained and described in Chapter 3. Its complete control scheme as well as its inner and outer control loops are presented. Parameter tuning is also given. Then, an extensive simulation study is given in Chapter 4. Starting, speed reversal and step loading of the chosen SM is done. Comparative analysis between the novel and the known observer and between the novel and the known nonlinear control system are included. Finally, conclusion with main contributions and discussion is also given.

2 Deterministic Observer

2.1 Dynamical System

In the [11-12] SM model with damper winding fluxes is given. Observability of the damper winding fluxes have been proved and various observers are presented. Full order observers need information about load torque. Reduced order observer does not have any convergence coefficients and is practically a pure integration. In the case of parameter variation, reduced order observer will lose its precision. Due to this, a novel observer is obtained. From the SM model [11] [12] with damper winding fluxes the following dynamical equations are extracted:

$$\frac{di_d}{dt} = a_1 i_d + a_2 i_f + a_3 i_q \omega + a_4 \psi_D + a_5 \psi_Q \omega + a_6 u_d + a_7 u_f \quad \text{(1a)}$$

$$\frac{d\psi_D}{dt} = c_1 i_d + c_2 i_f + c_3 \psi_D \quad \text{(1b)}$$

$$\frac{di_q}{dt} = d_1 i_q + d_2 i_d \omega + d_3 i_f \omega + d_4 \omega \psi_D + d_5 \psi_Q + d_6 u_q \quad \text{(1c)}$$

$$\frac{d\psi_Q}{dt} = f_1 i_q + f_2 \psi_Q \quad \text{(1d)}$$

where u, i, ψ are current, voltage, and magnetic flux noted in rotor (dq) coordinates,

ω is rotor speed,

and coefficients from a_1 to f_2 are given in Appendix A.

2.2 Observer

Deterministic observer of the system given in (1) is proposed:

$$\frac{d\widehat{i_d}}{dt} = a_1 i_d + a_2 i_f + a_3 i_q \omega + a_4 \widehat{\psi_D} + a_5 \widehat{\psi_Q} \omega + a_6 u_d + a_7 u_f + k_{11} e_1 \quad \text{(2a)}$$

$$\frac{d\widehat{\psi_D}}{dt} = c_1 i_d + c_2 i_f + c_3 \widehat{\psi_D} + k_{21} e_1 + k_{22} e_3 \tag{2b}$$

$$\frac{d\widehat{\iota_q}}{dt} = d_1 i_q + d_2 i_d \omega + d_3 i_f \omega + d_4 \omega \widehat{\psi_D} + d_5 \widehat{\psi_Q} + d_6 u_q + k_{31} e_3 \tag{2c}$$

$$\frac{d\widehat{\psi_Q}}{dt} = f_1 i_q + f_2 \widehat{\psi_Q} + k_{41} e_1 + k_{42} e_3 \tag{2d}$$

where state errors are given:

$$e_1 = i_d - \widehat{\iota_d}; \ \ e_2 = \psi_D - \widehat{\psi_D}; \ e_3 = i_q - \widehat{\iota_q}; \ e_4 = \psi_Q - \widehat{\psi_Q}$$

and convergence coefficients:

$$k_{11}; \ k_{21}; \ k_{22}; \ k_{31}; \ k_{41}; \ k_{42}$$

The stability of the observer (2) is proved according to the positive definite Lyapunov function:

$$V = \frac{e_1^2}{2} + \frac{e_2^2}{2} + \frac{e_3^2}{2} + \frac{e_4^2}{2} \tag{3}$$

With (1) – (2), an error dynamics of the observer is:

$$\frac{de_1}{dt} = a_4 e_2 + a_5 \omega e_4 - k_{11} e_1 \tag{4a}$$

$$\frac{de_2}{dt} = c_3 e_2 - k_{21} e_1 - k_{22} e_3 \tag{4b}$$

$$\frac{de_3}{dt} = d_4 \omega e_2 + d_5 e_4 - k_{31} e_3 \tag{4c}$$

$$\frac{de_4}{dt} = f_2 e_4 - k_{41} e_1 - k_{42} e_3 \tag{4d}$$

Using error dynamics (4), Lyapunov function (3) derivation becomes:

$$\dot{V}_1 = a_4 e_1 e_2 + a_5 \omega e_1 e_4 - k_{11} e_1^2 + c_3 e_2^2 - k_{21} e_1 e_2 - k_{22} e_2 e_3 +$$
$$+ d_4 \omega e_2 e_3 + d_5 e_3 e_4 - k_{31} e_3^2 + f_2 e_4^2 - k_{41} e_1 e_4 - k_{42} e_3 e_4 \tag{5a}$$

After some algebra:

$$\dot{V}_1 = e_1 e_2 (a_4 - k_{21}) + e_1 e_4 (a_5 \omega - k_{41}) - k_{11} e_1^2 + c_3 e_2^2 +$$
$$+ e_2 e_3 (d_4 \omega - k_{22}) + e_3 e_4 (d_5 - k_{42}) - k_{31} e_3^2 + f_2 e_4^2 \tag{5b}$$

If the convergence coefficients are defined:

$$k_{21} = a_4 \, ; k_{41} = a_5 \omega \, ; k_{22} = d_4 \omega \, ; k_{42} = d_5$$

Lyapunov function derivation becomes:

$$\dot{V} = -k_{11} e_1^2 + c_3 e_3^2 - k_{31} e_3^2 + f_2 e_5^2 \tag{5c}$$

The parameters c_3 and f_2 are always negative due to character of the damper windings [11] [12]. If k_{11} and k_{31} coefficients are defined to be positive:

$$k_{11} = k_{31} = 40$$

then all elements of the expression (5.c) are negative definite, and Lyapunov function derivation is obtained:

$$\dot{V} < 0 \tag{5d}$$

According to Lyapunov, positive definite Lyapunov function (3) with its negative definite derivation (5d) assures asymptotic stability of the observer (2).

3 Linear Control System

3.1 Introduction

To obtain linear control system, stator field oriented vector control principle is used. Electromagnetic torque is controlled by the referent stator current component i_T. Magnetic flux is controlled by the i_ψ referent stator current component that is oriented in the stator field direction. To transfer from stator to rotor coordinates, the Park transformations is applied:

$$i_{dref} = i_{\psi ref} cos\delta + i_{Tref} sin\delta \tag{6a}$$

$$i_{qref} = -i_{\psi ref} sin\delta + i_{Tref} cos\delta \tag{6b}$$

It could be seen that (6) needs calculation of the load angle δ. Using observed (2) damper winding fluxes, stator fluxes could be easily obtained. Then, dividing stator flux components, load angle could be easily obtained:

$$\delta = arc\, tg \frac{\psi_q}{\psi_d} \tag{7}$$

where ψ_d, ψ_q magnetic flux components of the stator winding.

In the Figure 1. The scheme of control system is given. It is cascaded system based on the stator current component inner loops and rotor speed and magnetic flux outer loops. Using stator and rotor currents and voltages, as well as rotor speed measurements, the control system is built. Controllers generate reference voltage that is applied onto the inverter by space vector modulation. Testing of the proposed control method is done for the exemplar SM which parameters are given in the Table 1. Computed dynamical system (1) for the used SM is given in Appendix B.
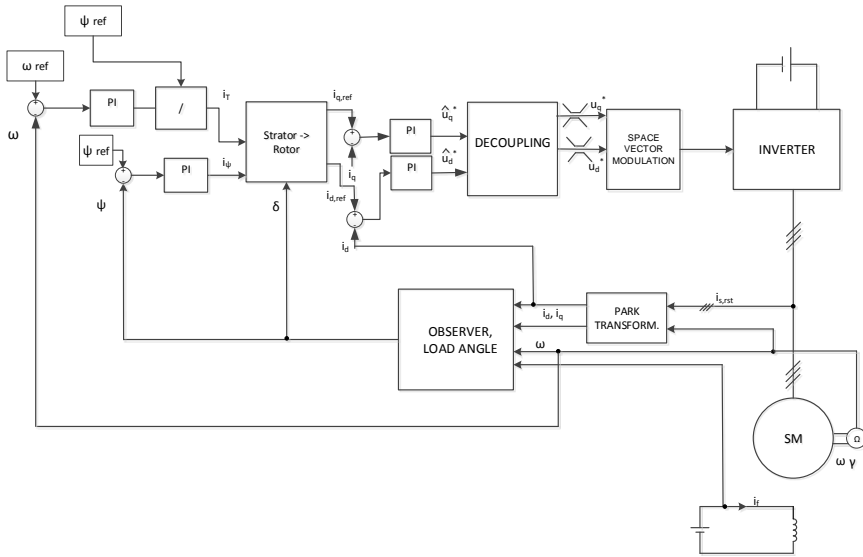
Figure 1

Control scheme

Table 1

Synchronous machine parameters

Power	S_n (kVA)	8.1		Rotor w. resistance	R_f (p.u.)	0.0612
Voltage	U_n (V)	400		Rotor w. leak. ind.	$L_{\sigma f}$ (p.u.)	0.18
Pole pairs	p	2		Damper w. res. d -axis	R_{kD} (p.u.)	0.159
Frequency	f_n (Hz)	50		Damper w. leak.ind. d-axis	$L_{\sigma kD}$ (p.u.)	0.117
Stator w. resistance	R_s (p.u.)	0.082		Damper w. res. q -axis	R_{kQ} (p.u.)	0.242
Stator w. leak. ind.	L_σ (p.u.)	0.072		Damper w. leak.ind. q-axis	$L_{\sigma kQ}$ (p.u.)	0.162
Mutual ind. d - axis	L_{md} (p.u.)	1.728		Inertia constant	H (s)	0.14
Mutual ind. q - axis	L_{mq} (p.u.)	0.823				

3.2   Stator Current Control

Using (1a) and (1c), dynamics of the stator current components could be written:

$$\frac{1}{a_6}\frac{di_d}{dt} - \frac{a_1}{a_6}i_d = u_d + e_d \qquad (8a)$$

$$\frac{1}{d_6}\frac{di_q}{dt} - \frac{d_1}{d_6}i_q = u_q + e_q \qquad (8b)$$

where:

$$e_d = \frac{a_2 i_f + a_3 i_q \omega + a_4 \psi_D + a_5 \psi_Q \omega + a_7 u_f}{a_6} \qquad (9a)$$

$$e_q = \frac{d_2 i_d \omega + d_3 i_f \omega + d_4 \omega \psi_D + d_5 \psi_Q}{d_6} \qquad (9a)$$

To obtain simplification, the following variables are introduced:

$$\hat{u}_d = u_d - e_d \qquad (10a)$$

$$\hat{u}_q = u_q - e_q \qquad (10b)$$

Components e_d, e_q are later used for obtaining decoupling, while stator current dynamics become linear differential equations of the first order:

$$\hat{u}_d = a i_d + \frac{1}{a_6}\frac{di_d}{dt} \qquad (11a)$$

$$\hat{u}_q = d i_q + \frac{1}{d_6}\frac{di_q}{dt} \qquad (11b)$$

where:

$$a = -\frac{a_1}{a_6}; \quad d = -\frac{d_1}{d_6}$$

When the transformation into the Laplace domain is done, (11) become:

$$G_1(s) = \frac{I_d(s)}{\widehat{U}_d(s)} = \frac{\frac{1}{a}}{\frac{1}{aa_6}s+1} \qquad (12a)$$

$$G_2(s) = \frac{I_q(s)}{\widehat{U}_q(s)} = \frac{\frac{1}{d}}{\frac{1}{dd_6}s+1} \qquad (12b)$$

if:

$$k_{p1} = \frac{1}{a}; \quad \tau_{p1} = \frac{1}{aa_6}; \quad k_{p2} = \frac{1}{d}; \quad \tau_{p2} = \frac{1}{dd_6}$$

stator current transfer functions could be noted:

$$G(s) = \frac{k_p}{\tau_p s+1} \qquad (13)$$

Using IMC the transfer function of the IMC control of the stator current components could be derived:

$$G_c(s) = \frac{k_p}{k_p \lambda}\frac{\tau_p s+1}{\tau_p s} \qquad (14)$$

If (14) is compared to a classical PI transfer function form:

$$G_{PI}(s) = k_c \frac{\tau_I s+1}{\tau_I s} \qquad (15)$$

it could be concluded that IMC PI controller parameters are:

$$k_c = \frac{\tau_p}{k_p \, \lambda} \tag{16a}$$

$$\tau_I = \tau_p \tag{16b}$$

In the d axis the i_d control is obtained. Proportional and integral parameters are given:

$$k_{c1} = \frac{\frac{1}{a \, a_6}}{\frac{1}{a} \lambda_1} = \frac{1}{\lambda_1 \, a_6} \tag{17a}$$

$$k_{I1} = \frac{k_{c1}}{\tau_{I1}} = \frac{k_{c1}}{\frac{1}{a \, a_6}} \tag{17b}$$

In the q axis the i_q control is obtained. Proportional and integral parameters are given:

$$k_{c2} = \frac{\frac{1}{d \, d_6}}{\frac{1}{d} \lambda_2} = \frac{1}{\lambda_2 \, d_6} \tag{18a}$$

$$k_{I2} = \frac{k_{c1}}{\tau_{I2}} = \frac{k_{c1}}{\frac{1}{d \, d_6}} \tag{18b}$$

where λ_1, λ_2 are used to obtain tuning of the current loops.

3.5   Tuning

Using SM parameters given in Table 1, controller gains could be computed. At first, gains for the current controls are:

$$k_{c1} = \frac{0,14}{\lambda_1} \tag{19a}$$

$$k_{I1} = \frac{0,14}{0,824 \, \lambda_1} \tag{19b}$$

$$k_{c2} = \frac{0,21}{\lambda_2} \tag{19c}$$

$$k_{I2} = \frac{0,21}{0,83 \, \lambda_2} \tag{19d}$$

After few iterations λ_1, λ_2 are set as:

$$\frac{1}{\lambda_1} = 35 \; ; \frac{1}{\lambda_2} = 28$$

Then stator current gains could be finally calculated:

$$k_{c1} = 5 \; ; k_{I1} = 6$$

$$k_{c2} = 6 \; ; k_{I2} = 7$$

Then, using stator current gains, outer control loops are tuned using following procedure:

1. Simulations with step up speed reference
   a. $K_{p\psi}$ is increased enough to obtain the control of the stator flux and to achieve the electromagnetic torque has no oscillations. $K_{p\omega}$ is increased until the rotor speed could reach its nominal value. $K_{i\omega}, K_{p\psi}$ are set on zero value.
   b. $K_{p\omega}$ is then increased as much as it is needed for the rotor speed control to reach its critical point (oscilations)
   c. Using Ziegler-Nichols method, parameters $K_{p\omega}, K_{i\omega}$ are callculated from the simulation results of the b.
2. Simulations with ramping rotor speed (real) reference:
   a. $K_{p\omega}, K_{i\omega}$ are used as calculated in 1.c and $K_{p\psi}$ is decreased as much as possible. Rotor speed tracking has to remain precise.
   b. Magnetic flux stationary error is corrected by putting $K_{p\psi}$ on some value (ex. $K_{p\psi} = K_{i\psi}$).
   c. Finally, $K_{i\omega}$ could be reduced until the control remain precise.

After the procedure, the outer loop gains are set as:

$$K_{p\omega} = 120, K_{i\omega} = 150$$

$$K_{p\psi} = 30, K_{i\psi} = 30$$

4   Comparative Simulation

4.1   Introduction

Matlab Simulink model of the DC/AC inverter drive is built. Inverter, VSI (Voltage Source Inverter) type, is used to obtain SM drive. Observer based linear control system comparison with nonlinear control system [11-12] is obtained. Load torque is assumed to be unknown disturbance for the linear control system. For the nonlinear control system, load torque is assumed to be known and its value is taken directly from the model. Therefore, some advantage is given to the nonlinear control system.

Control systems have been put in the same simulation model and the following SM dynamics have been obtained: starting under loaded condition, speed reversal under no load condition and step loading.

The aim is to control the rotor speed while maintaining stator flux at its nominal value. Tracking control has to be obtained, while the rotor speed reference is ramp. Control is obtained only through the stator voltage, while the rotor voltage is kept on its nominal value.

Parameters of the novel linear control system PI controllers are set as is given in the Chapter 3.5, while the parameters of the nonlinear control systems are set:

$$K_\omega = 90, K_{torque} = 20, K_\psi = 25$$

4.2 Starting

During starting process, load torque increase proportional to the rotor speed. When the nominal speed is reached at 1.5 s, load torque reaches its nominal value of about 0.75 p.u. as it is given in Figure 8.
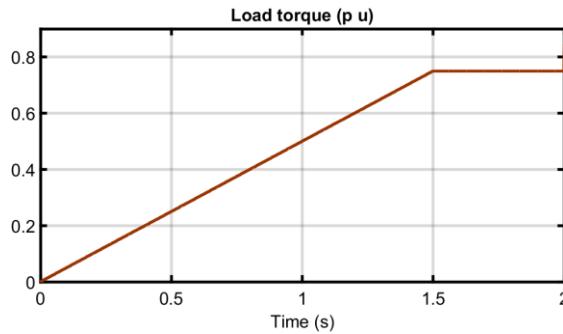

Figure 2

Starting – Load torque

In the Figure 3 performance of the damper winding flux observer (2) is shown. The observer is very precise.

Then, in the Figure 4, performances of both control systems are given. Precision of the rotor speed control is about equal, but precision of the stator flux control is better in the case of novel linear control.
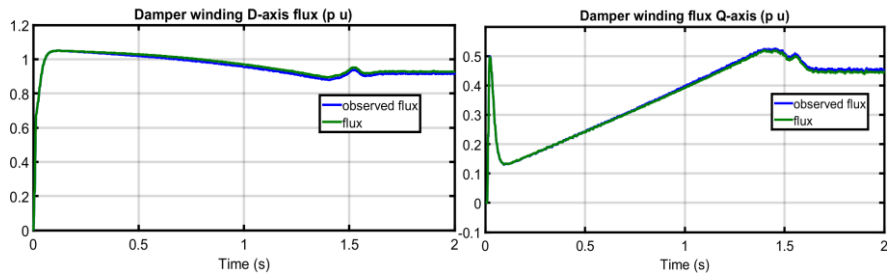
Figure 3

Starting – Observer performance
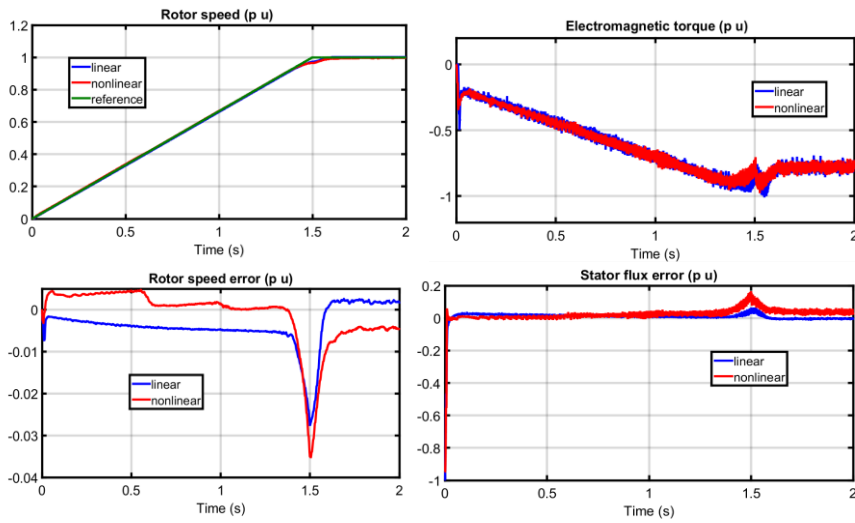
Figure 4
Starting - Control performance

4.3   Speed Reversal

Speed reversal is obtained without load torque. In that case, SM starting is shorter and ends at 1.0 s. Observer performance is again precise as is given in Figure 5.
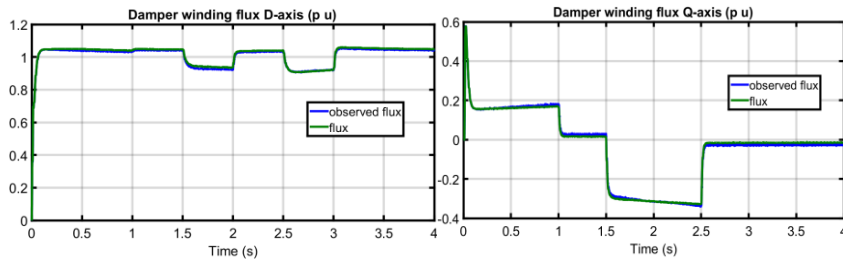

Figure 5
Speed reversal – Observer performance

Precision of the rotor speed control is about equal, but precision of the stator flux control is better in the case of novel linear control as is shown in Figure 6.
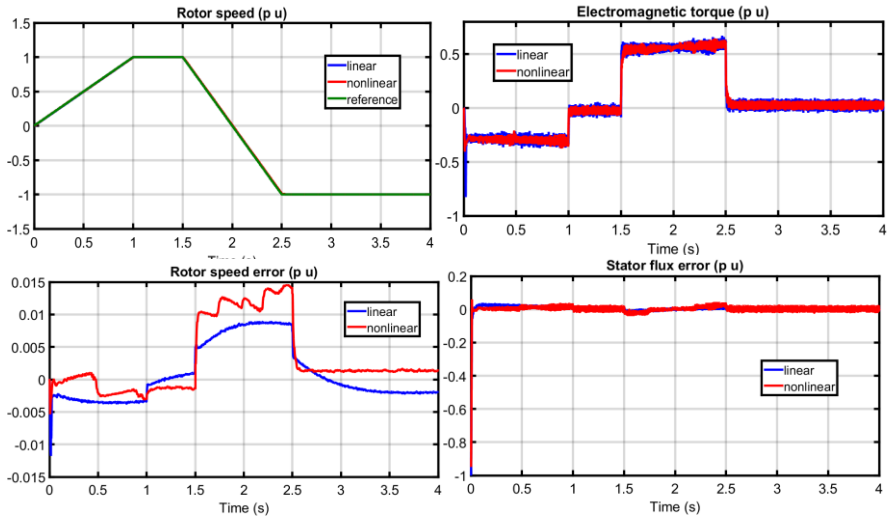
Figure 6

Speed reversal - Control performance

4.4   Step Loading

SM starting is obtained without loading. After reaching the nominal speed, the step loading and unloading (Figure 7) has been applied. The step has the value of the SM nominal load.
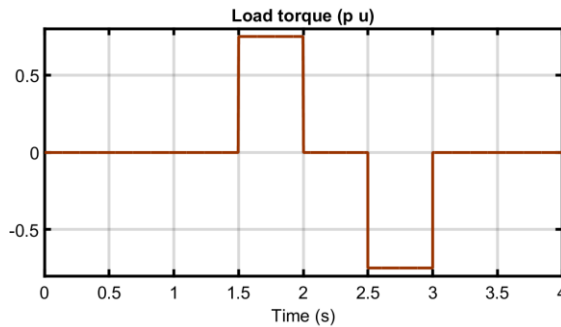

Figure 7

Step loading – Load torque

In spite of great load changes, observer performance is again precise as is shown in Figure 8.
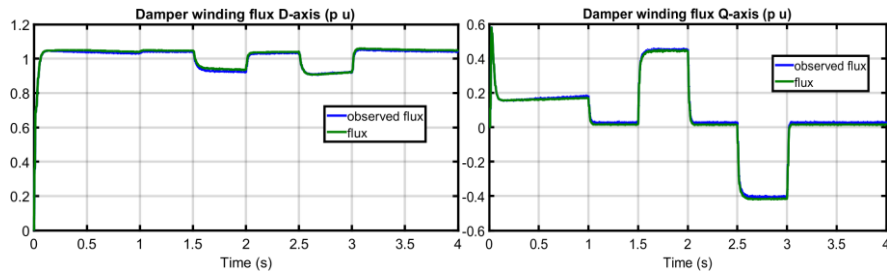
Figure 8
Step loading – Observer performance

Precision of the rotor speed control is about equal, but precision of the stator flux control is better in the case of novel linear control as is shown in Figure 9.
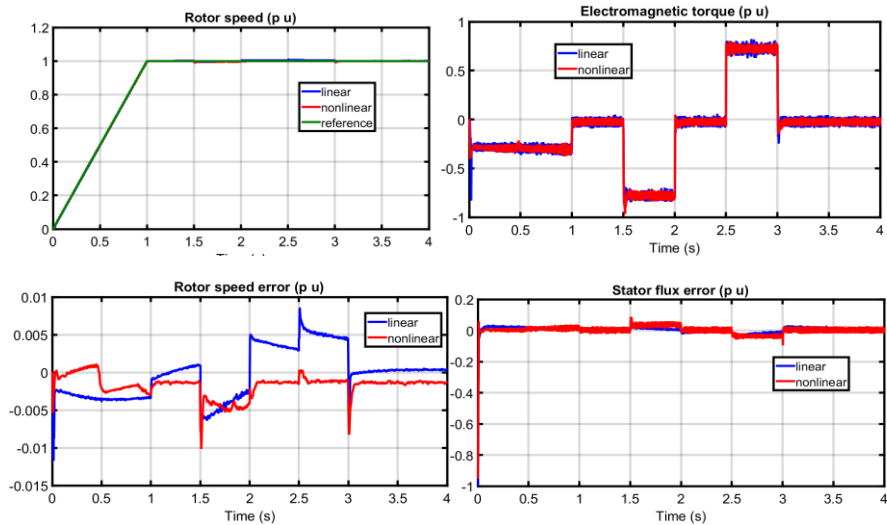

Figure 9
Step loading - Control performance

4.5 Observer Comparison

Operation of the novel and pure integration observer given in [11] [12] have been analyzed. Observers are applied in the same drive system and results for the starting, speed reversal and step loading have been given. Due to computational error there is some drift in dynamics of the pure integration observer. It especially occurs in D-axes as is shown during the starting process (Figure 10). Error of the novel observer is negligible.
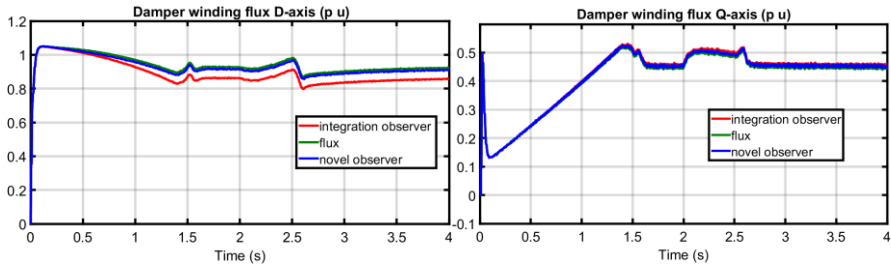
Figure 10
Starting – observer comparison

In the Figure 11 results for the dynamics of the speed reversal have been shown. Both observers perform precise operation, but better results are achieved by the novel flux observer.
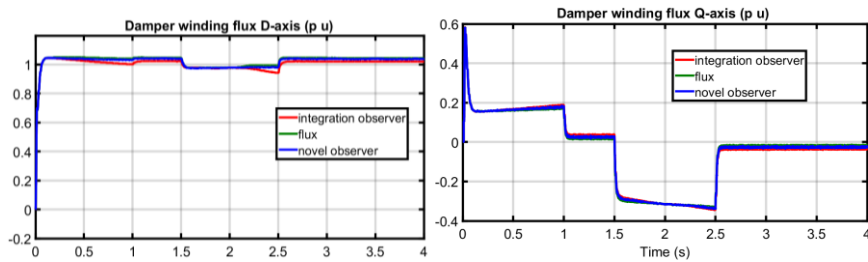

Figure 11
Speed reversal – observer comparison

During the step loading (Figure 12) some drift in D-axis flux could be again seen in pure integration observer, while the novel observer dynamics are precise.
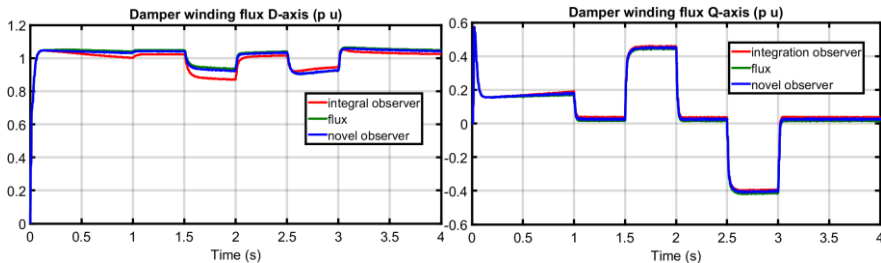

Figure 12
Step loading – observer comparison

4.6   Controller Comparison

Obtaining speed reversal simulations, influence of the controller has been analyzed. At first it is shown that performance of the nonlinear controller could not be improved much if the integration observer [11] [12] is replaced by the

novel observer. As is shown in Figure 13, novel observer reduces nonlinear control performance error only for a bit.
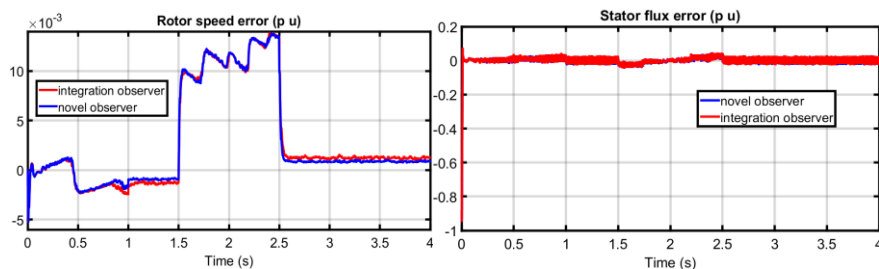

Figure 13
Speed reversal – nonlinear controller using different observers

Performance of the novel linear control has been tested when it uses different observers. Due to the error of the integration observer, rotor speed error increases as it is shown in Figure 14.
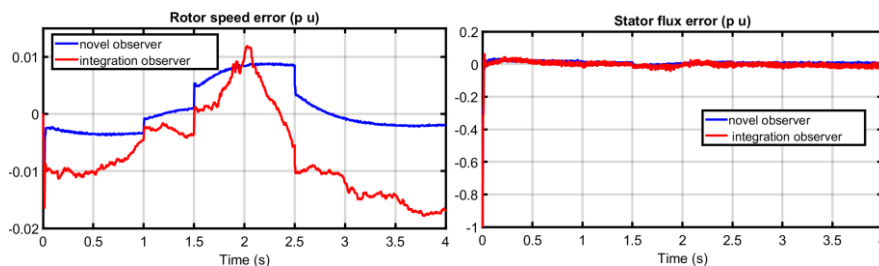

Figure 14
Speed reversal – novel controller using different observers

It could be concluded that novel linear control backed by the novel flux observer gives the best control performance.

4.7   Robustness of the Control System

To obtain robustness-testing, variation of the SM parameters has been done. Step loading simulations in the cases of inductances increase and inductance decrease have been obtained. In the case of the main SM inductance 15 percent increase, results are shown in the Figure 15. During the load torque step-up, nonlinear control performance deteriorates. Novel linear control performance remains precise.
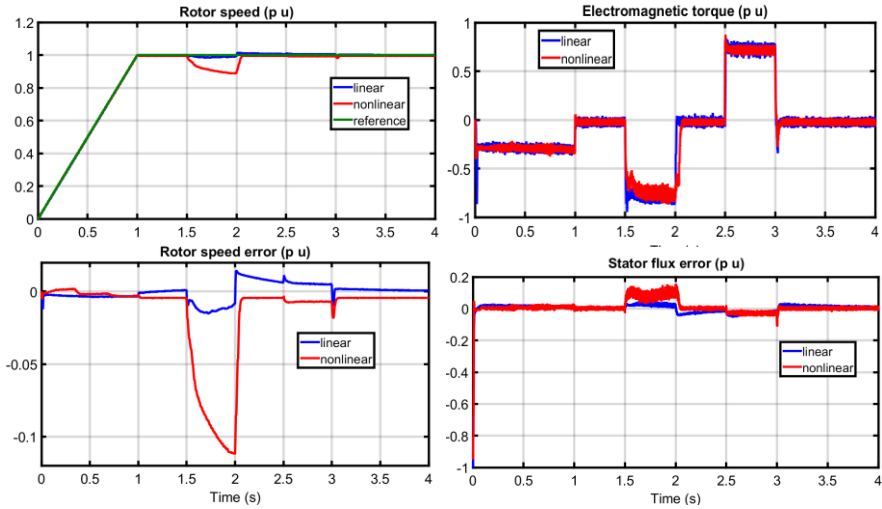
Figure 15
Step loading – increased inductance

In the case of the main SM inductance 15 percent decrease, results are shown in the Figure 16. Novel linear control system shows better results in both: rotor speed and stator flux control.
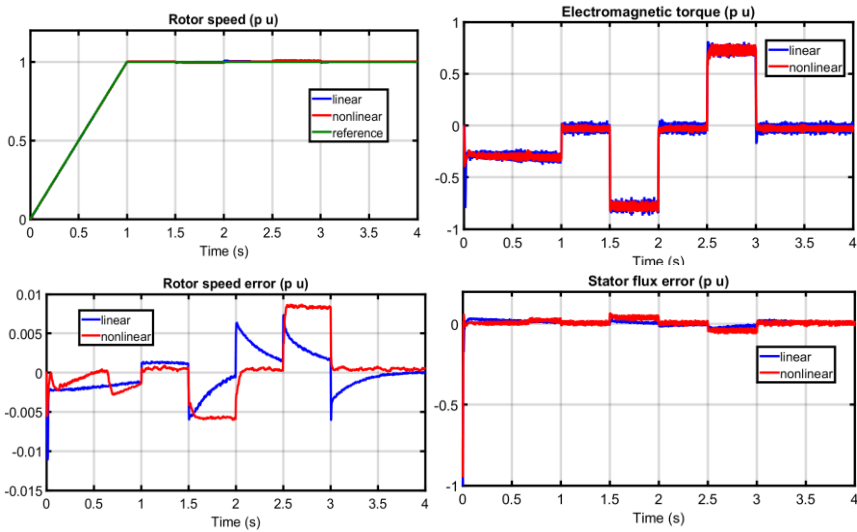

Figure 16
Step loading – decreased inductance

Conclusions

There is still room for improvement, in the research field of SM control. Linear control studies usually fail to take into consideration all complexities of the SM dynamical system. Nonlinear control studies are usually predictive control laws that need to know all system states, inputs and disturbances. Specially, precise information about the load torque is sometimes hard to obtain.

Based on the given deterministic observer and linear control analysis, a novel control method has been presented in this work. Without any need for predictive information and without any knowledge about load torque the novel control systems obtains high performance.

To obtain adequate comparison, simulation studies for an exemplar SM have been done. Dynamical responses in the cases of SM starting, speed reversal, and step loading have been compared to results of the nonlinear control. Results show that novel deterministic observer gives better results than the existing one. It is also shown that novel control gives equal or better results than nonlinear control. Finally, it could be concluded, that due to all mentioned advantages, the novel control system is preferred for use in praxis.

Acknowledgement

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Appendix A

Coefficients of synchronous machine dynamical model given in (1):

$$a_1 = \frac{L_f L_{md}{}^2 R_D - L_{md}{}^3 R_D - L_D{}^2 L_f R_s + L_D L_{md}{}^2 R_s}{L_D\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)}$$

$$a_2 = \frac{-L_f L_{md}{}^2 R_D + L_{md}{}^3 R_D + L_D{}^2 L_{md} R_f - L_D L_{md}{}^2 R_f}{L_D\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)}$$

$$a_3 = \frac{L_D{}^2 L_f L_{mq}{}^2 - L_D L_{md}{}^2 L_{mq}{}^2 - L_D{}^2 L_f L_q L_Q + L_D L_{md}{}^2 L_q L_Q}{L_D L_Q\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)}$$

$$a_4 = \frac{L_f L_{md} L_Q R_D - L_{md}{}^2 L_Q R_D}{L_D L_Q\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)}$$

$$a_5 = \frac{L_D{}^2 L_f L_{mq} - L_D L_{md}{}^2 L_{mq}}{L_D L_Q\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)}$$

$$a_6 = \frac{L_D{}^2 L_f L_Q - L_D L_{md}{}^2 L_Q}{L_D L_Q\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)}$$

$$a_7 = \frac{-L_D{}^2 L_{md} L_Q + L_D L_{md}{}^2 L_Q}{L_D L_Q\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)}$$

$$c_1 = -\frac{L_{md} R_D}{L_D}$$

$$c_2 = \frac{L_{md} R_D}{L_D}$$

$$c_3 = -\frac{R_D}{L_D}$$

$$d_1 = \frac{-L_D L_{mq}{}^2 R_Q + L_D L_Q{}^2 R_s}{L_D L_Q\left(-L_{mq}{}^2 + L_q L_Q\right)}$$

$$d_2 = \frac{-L_d L_D L_Q{}^2 + L_{md}{}^2 L_Q{}^2}{L_D L_Q\left(-L_{mq}{}^2 + L_q L_Q\right)}$$

$$d_3 = \frac{L_D L_{md} L_Q{}^2 - L_{md}{}^2 L_Q{}^2}{L_D L_Q \left(-L_{mq}{}^2 + L_q L_Q\right)}$$

$$d_4 = \frac{L_{md} L_Q}{L_D \left(-L_{mq}{}^2 + L_q L_Q\right)}$$

$$d_5 = \frac{-L_{mq} R_Q}{L_Q \left(-L_{mq}{}^2 + L_q L_Q\right)}$$

$$d_6 = \frac{-L_Q}{\left(-L_{mq}{}^2 + L_q L_Q\right)}$$

$$f_1 = -\frac{L_{mq} R_Q}{L_Q}$$

$$f_2 = -\frac{R_Q}{L_Q}$$

Appendix B

Computed dynamical system (1) of the used synchronous machine:

$$\frac{di_d}{dt} = -1{,}2\, i_d - 0{,}45\, i_f + 1{,}48\, i_q \omega + 0{,}36\, \psi_D + 5{,}96\, \psi_Q \omega + 7{,}13\, u_d - 2{,}7\, u_f$$

$$\frac{d\psi_D}{dt} = 0{,}15\, i_d + 0{,}15\, i_f - 0{,}09\, \psi_D$$

$$\frac{di_q}{dt} = -1{,}21\, i_q - 0{,}88\, i_d \omega - 0{,}53\, i_f \omega - 4{,}52\omega\psi_D + 0{,}9\, \psi_Q + 4{,}82\, u_q$$

$$\frac{d\psi_Q}{dt} = 0{,}2\, i_q - 0{,}25\, \psi_Q$$