Chapter

Synchronous Machine Nonlinear Control System Based on Feedback Linearization and Deterministic Observers

Marijo Šundrica

Abstract

A classical linear control system of the SM is based on PI current controllers. Due to SM nonlinearity, with such control system, it is not possible to obtain independent torque and flux control. To overcome this obstacle, a nonlinear control system can be used. Due to unknown damper winding state variables, an observer has to be made. In this work, observers for damper winding currents and damper winding fluxes are presented. Then, based on nonlinear theory, control law with feedback linearization method is obtained. Also, a comparison of the proposed and classical control system is done. For the classical control system, field-oriented control with internal model and symmetrical optimum principles is used. To verify the proposed algorithm, extensive simulation analysis of voltage source inverter drive is made. Processor in the loop testing has been also done.

Keywords: synchronous machine, observers, damper winding, nonlinear control, feedback linearization, voltage source inverter, processor in the loop

1. Introduction

For synchronous machine (SM) with damper winding and separate excitation winding, it is not unusual to operate as an AC drive system.

In hydropower generation, sometimes, there is demand for SM to work in compensating or pumping operation mode. Then, at least motor starting of the SM has to be assured. The most sophisticated starting process is synchronous starting also called variable speed operation. It is obtained by frequency converter, whether by current source inverter (CSI) or voltage source inverter (VSI). In wind power generation, SM could be also used. Then, it is also used for variable speed operation.

Except from SM used in power generation, SM could be also used as AC drive systems in industrial applications with high power demand such as coal mines, metal and cement industries. It is also used for ship propulsion.

AC drive system for SM is traditionally done by CSI topology with thyristors. Although CSI has some advantages, VSI topology has been also used lately. It is mainly due to development of fully controllable switches (IGBT, GTO, etc.) that are nowadays also used for high power demands. Due to its controllability, PWM could be easily applied on VSI topology.

Because of the salient poles, a large number of coupled variables and high nonlinearity, the SM is a complex dynamic system with a number of unknown state variables. To obtain its control, classical system uses PI controllers for stator *dq* current components control. But due to SM's complexity, it is not possible to obtain fully decoupled torque and flux control. Namely, change of any current component necessary changes both; torque and flux. Another difficulty is unknown damper winding current.

This work examines a novel control method for variable speed operation of a SM. To overcome mentioned obstacles arisen from SM complexity, novel control will be nonlinear. VSI topology is suitable to be used with this novel control. The goal of the control system is to obtain high performance speed tracking system. To achieve this, it is necessary to have an adequate observer for damper winding states, as is similarly done in induction motor drive system [1].

There are not many studies regarding SMs AC drive system; whether with linear or nonlinear control. Classical vector control is rotor field oriented control used with the following assumption: if the flux is constant, the q-current component can control electromagnetic torque. For induction motor drives this assumption holds, but if this method is used for SM control, the q-current component will essentially change the flux [2]. It is said that control is coupled and this is why SM vector control is not efficient enough. There are few ideas on how to solve this problem. In [3] stator flux orientation control is used. With this orientation, through excitation current compensation, better flux control is obtained. Unfortunately, a control system with many calculations (coordinate transformations, PI controllers, and other) has to be used. Also, damper winding current affect has not been taken into account.

Regarding nonlinear control SM applications, a few methods are used: backstepping [4], passivity [5] and adaptive Lyapunov based [6]. The passive method [5] fails to give better results and the backstepping [4] method fails to take damper windings into consideration. In [6] new algorithms are proposed, but besides of their complexity, a control in excitation system also has to be used.

The aim of this work is to find deterministic observer for a SM and to use it by nonlinear control law. Parameter adaptivity and load torque estimation is also considered. Finally, high performance VSI drive system without excitation system control is thus obtained.

2. Observers

In this section observers for SM are presented. Starting from the SM dynamic system, damper winding deterministic observers are made. At first, an observer with damper winding currents is given. Then, full order and reduced order observers for damper winding fluxes are presented. Observability analysis for the full order observer is given. Stability is approved with Lyapunov stability theory.

Finally, load torque estimation system is presented. Observability of the expanded system is analyzed and the model reference adaptive system is given.

2.1 Damper winding current observers

Synchronous machine can be described as a dynamic system of six state variables. If five of them are set to be SM currents and the sixth is rotor speed, SM dynamic system is:

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_f \\ \dot{i}_D \\ \dot{i}_q \\ \dot{i}_Q \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} a_1' i_d + a_2' i_q\omega + a_3' i_Q\omega + a_4' i_f + a_5' i_D + a_6' u_d + a_7' u_f \\ b_1' i_d + b_2' i_q\omega + b_3' i_Q\omega + b_4' i_f + b_5' i_D + b_6' u_d + b_7' u_f \\ c_1' i_d + c_2' i_q\omega + c_3' i_Q\omega + c_4' i_f + c_5' i_D + c_6' u_d + c_7' u_f \\ d_1' i_q + d_2' i_d\omega + d_3' i_f\omega + d_4' i_D\omega + d_5' i_Q + d_6' u_q \\ f_1' i_q + f_2' i_d\omega + f_3' i_f\omega + f_4' i_D\omega + f_5' i_Q + f_6' u_q \\ j_1' i_d i_q + j_2' i_f i_q + j_3' i_q i_D + j_4' i_d i_Q + j_5' T_L \end{bmatrix} \quad (1)$$

To obtain high performance drive all SM states should be known. Since damper winding currents are normally not measured, to make all states available, an observer has to be made. In Eq. (2) is an expression of the SM deterministic observer with damper winding currents.

$$\begin{bmatrix} \dot{\hat{i}}_d \\ \dot{\hat{i}}_f \\ \dot{\widehat{i_D}} \\ \dot{\hat{i}}_q \\ \dot{\widehat{i_Q}} \\ \dot{\hat{\omega}} \end{bmatrix} = \begin{bmatrix} a_1' i_d + a_2' i_q\omega + a_3' \widehat{i_Q}\omega + a_4' i_f + a_5' \widehat{i_D} + a_6' u_d + a_7' u_f \\ b_1' i_d + b_2' i_q\omega + b_3' \widehat{i_Q}\omega + b_4' i_f + b_5' \widehat{i_D} + b_6' u_d + b_7' u_f \\ c_1' i_d + c_2' i_q\omega + c_3' \widehat{i_Q}\omega + c_4' i_f + c_5' \widehat{i_D} + c_6' u_d + c_7' u_f \\ d_1' i_q + d_2' i_d\omega + d_3' i_f\omega + d_4' \widehat{i_D}\omega + d_5' \widehat{i_Q} + d_6' u_q \\ f_1' i_q + f_2' i_d\omega + f_3' i_f\omega + f_4' \widehat{i_D}\omega + f_5' \widehat{i_Q} + f_6' u_q \\ j_1' i_d i_q + j_2' i_f i_q + j_3' i_q \widehat{i_D} + j_4' i_d \widehat{i_Q} + j_5' T_L \end{bmatrix} + \begin{bmatrix} k_{11}' e_1 + k_{12}' e_2 + k_{14}' e_4 + k_{16}' e_6 \\ k_{21}' e_1 + k_{22}' e_2 + k_{24}' e_4 + k_{26}' e_6 \\ k_{31}' e_1 + k_{32}' e_2 + k_{34}' e_4 + k_{36}' e_6 \\ k_{41}' e_1 + k_{42}' e_2 + k_{44}' e_4 + k_{46}' e_6 \\ k_{51}' e_1 + k_{52}' e_2 + k_{54}' e_4 + k_{56}' e_6 \\ k_{61}' e_1 + k_{62}' e_2 + k_{64}' e_4 + k_{66}' e_6 \end{bmatrix} \quad (2)$$

Observed values are noted with "^"; e_x are errors, differences between measured and observed value; while k_{xy} are adaptive coefficients used to obtain the convergence.

If the observer in Eq. (2) is made only with observed values and errors [7], damper current observer Eq. (3) is obtained.

$$\begin{bmatrix} \dot{\hat{i}}_d \\ \dot{\hat{i}}_f \\ \dot{\widehat{i_D}} \\ \dot{\hat{i}}_q \\ \dot{\widehat{i_Q}} \\ \dot{\hat{\omega}} \end{bmatrix} = \begin{bmatrix} a_1' \hat{i}_d + a_2' \hat{i}_q\hat{\omega} + a_3' \widehat{i_Q}\hat{\omega} + a_4' \hat{i}_f + a_5' \widehat{i_D} + a_6' u_d + a_7' u_f \\ b_1' \hat{i}_d + b_2' \hat{i}_q\hat{\omega} + b_3' \widehat{i_Q}\hat{\omega} + b_4' \hat{i}_f + b_5' \widehat{i_D} + b_6' u_d + b_7' u_f \\ c_1' \hat{i}_d + c_2' \hat{i}_q\hat{\omega} + c_3' \widehat{i_Q}\hat{\omega} + c_4' \hat{i}_f + c_5' \widehat{i_D} + c_6' u_d + c_7' u_f \\ d_1' \hat{i}_q + d_2' \hat{i}_d\hat{\omega} + d_3' \hat{i}_f\hat{\omega} + d_4' \widehat{i_D}\hat{\omega} + d_5' \widehat{i_Q} + d_6' u_q \\ f_1' \hat{i}_q + f_2' \hat{i}_d\hat{\omega} + f_3' \hat{i}_f\hat{\omega} + f_4' \widehat{i_D}\hat{\omega} + f_5' \widehat{i_Q} + f_6' u_q \\ j_1' \hat{i}_d \hat{i}_q + j_2' \hat{i}_f \hat{i}_q + j_3' \hat{i}_q \widehat{i_D} + j_4' \hat{i}_d \widehat{i_Q} + j_5' T_L \end{bmatrix} + \begin{bmatrix} k_{11}' e_1 + k_{12}' e_2 + k_{14}' e_4 + k_{16}' e_6 \\ k_{21}' e_1 + k_{22}' e_2 + k_{24}' e_4 + k_{26}' e_6 \\ k_{31}' e_1 + k_{32}' e_2 + k_{34}' e_4 + k_{36}' e_6 \\ k_{41}' e_1 + k_{42}' e_2 + k_{44}' e_4 + k_{46}' e_6 \\ k_{51}' e_1 + k_{52}' e_2 + k_{54}' e_4 + k_{56}' e_6 \\ k_{61}' e_1 + k_{62}' e_2 + k_{64}' e_4 + k_{66}' e_6 \end{bmatrix} \quad (3)$$

There is a way to define adaptive coefficients in each one of the observers given in Eqs. (2) and (3) to prove their stability according to Lyapunov theory. The proof is extensive and is given in [8].

2.2 Damper winding full order flux observer

If the SM dynamics given in Eq. (1) is changed in a way that damper currents states are replaced with damper fluxes states, its dynamic system will become:

$$\begin{bmatrix} \dot{i_d} \\ \dot{i_f} \\ \dot{\psi_D} \\ \dot{i_q} \\ \dot{\psi_Q} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} a_1 i_d + a_2 i_f + a_3 i_q \omega + a_4 \psi_D + a_5 \psi_Q \omega + a_6 u_d + a_7 u_f \\ b_1 i_d + b_2 i_f + b_3 i_q \omega + b_4 \psi_D + b_5 \psi_Q \omega + b_6 u_d + b_7 u_f \\ c_1 i_d + c_2 i_f + c_3 \psi_D \\ d_1 i_q + d_2 i_d \omega + d_3 i_f \omega + d_4 \omega \psi_D + d_5 \psi_Q + d_6 u_q \\ f_1 i_q + f_2 \psi_Q \\ g_1 i_d i_q + g_2 i_f i_q + g_3 i_q \psi_D + g_4 i_d \psi_Q + g_5 T_L \end{bmatrix} \tag{4}$$

Using dynamic system given in Eq. (4) it is easier to obtain an observer. As it is shown in Eq. (5), full order observer with damper fluxes is:

$$\begin{bmatrix} \dot{\hat{i_d}} \\ \dot{\hat{i_f}} \\ \dot{\widehat{\psi_D}} \\ \dot{\hat{i_q}} \\ \dot{\widehat{\psi_Q}} \\ \dot{\hat{\omega}} \end{bmatrix} = \begin{bmatrix} a_1 i_d + a_2 i_f + a_3 i_q \omega + a_4 \widehat{\psi_D} + a_5 \widehat{\psi_Q} \omega + a_6 u_d + a_7 u_f + k_{11} e_1 \\ b_1 i_d + b_2 i_f + b_3 i_q \omega + b_4 \widehat{\psi_D} + b_5 \widehat{\psi_Q} \omega + b_6 u_d + b_7 u_f + k_{22} e_2 \\ c_1 i_d + c_2 i_f + c_3 \widehat{\psi_D} + k_{31} e_1 + k_{32} e_2 + k_{33} e_4 + k_{34} e_6 \\ d_1 i_q + d_2 i_d \omega + d_3 i_f \omega + d_4 \omega \widehat{\psi_D} + d_5 \widehat{\psi_Q} + d_6 u_q + k_{43} e_4 \\ f_1 i_q + f_2 \widehat{\psi_Q} + k_{51} e_1 + k_{52} e_2 + k_{53} e_4 + k_{54} e_6 \\ g_1 i_d i_q + g_2 i_f i_q + g_3 i_q \widehat{\psi_D} + g_4 i_d \widehat{\psi_Q} + g_5 T_L + k_{64} e_6 \end{bmatrix} \tag{5}$$

The analysis of the observability is based on nonlinear system weak observability concept [9]. According to reference [9], rank of the observability matrix O has to be checked.

Regarding the measured outputs, determinant of the arbitrarily chosen observability criterion matrices has to be calculated. The first criterion matrix O_1 is chosen:

$$O_1 = \begin{bmatrix} di_d \\ di_f \\ di_q \\ d\omega \\ d(L_f i_d) \\ d(L_f i_f) \end{bmatrix} = pt \begin{bmatrix} \frac{\partial L_f^0 i_d}{\partial i_d} & \frac{\partial L_f^0 i_d}{\partial i_f} & \frac{\partial L_f^0 i_d}{\partial \varphi_D} & \frac{\partial L_f^0 i_d}{\partial i_q} & \frac{\partial L_f^0 i_d}{\partial \varphi_Q} & \frac{\partial L_f^0 i_d}{\partial \omega} \\ \frac{\partial L_f^0 i_f}{\partial i_d} & \frac{\partial L_f^0 i_f}{\partial i_f} & \frac{\partial L_f^0 i_f}{\partial \varphi_D} & \frac{\partial L_f^0 i_f}{\partial i_q} & \frac{\partial L_f^0 i_f}{\partial \varphi_Q} & \frac{\partial L_f^0 i_f}{\partial \omega} \\ \frac{\partial L_f^0 i_q}{\partial i_d} & \frac{\partial L_f^0 i_q}{\partial i_f} & \frac{\partial L_f^0 i_q}{\partial \varphi_D} & \frac{\partial L_f^0 i_q}{\partial i_q} & \frac{\partial L_f^0 i_q}{\partial \varphi_Q} & \frac{\partial L_f^0 i_q}{\partial \omega} \\ \frac{\partial L_f^0 \omega}{\partial i_d} & \frac{\partial L_f^0 \omega}{\partial i_f} & \frac{\partial L_f^0 \omega}{\partial \varphi_D} & \frac{\partial L_f^0 \omega}{\partial i_q} & \frac{\partial L_f^0 \omega}{\partial \varphi_Q} & \frac{\partial L_f^0 \omega}{\partial \omega} \\ \frac{\partial L_f^1 i_d}{\partial i_d} & \frac{\partial L_f^1 i_d}{\partial i_f} & \frac{\partial L_f^1 i_d}{\partial \varphi_D} & \frac{\partial L_f^1 i_d}{\partial i_q} & \frac{\partial L_f^1 i_d}{\partial \varphi_Q} & \frac{\partial L_f^1 i_d}{\partial \omega} \\ \frac{\partial L_f^1 i_f}{\partial i_d} & \frac{\partial L_f^1 i_f}{\partial i_f} & \frac{\partial L_f^1 i_f}{\partial \varphi_D} & \frac{\partial L_f^1 i_f}{\partial i_q} & \frac{\partial L_f^1 i_f}{\partial \varphi_Q} & \frac{\partial L_f^1 i_f}{\partial \omega} \end{bmatrix} \tag{6}$$

After each matrix member of Eq. (6) is calculated [8], its determinant calculation gives:

$$Det(O_1) = -\frac{\omega L_{md} L_{mq} R_D}{L_D L_Q \left(L_d L_D L_f - L_d L_{md}{}^2 - L_D L_{md}{}^2 - L_f L_{md}{}^2 + 2L_{md}{}^3\right)} \tag{7}$$

The second criterion matrix O_2 is chosen:

$$O_2 = \begin{bmatrix} di_d \\ di_f \\ di_q \\ d\omega \\ d(L_f i_d) \\ d(L_f i_q) \end{bmatrix} = \begin{bmatrix} \frac{\partial L_f^0 i_d}{\partial i_d} & \frac{\partial L_f^0 i_d}{\partial i_f} & \frac{\partial L_f^0 i_d}{\partial \varphi_D} & \frac{\partial L_f^0 i_d}{\partial i_q} & \frac{\partial L_f^0 i_d}{\partial \varphi_Q} & \frac{\partial L_f^0 i_d}{\partial \omega} \\ \frac{\partial L_f^0 i_f}{\partial i_d} & \frac{\partial L_f^0 i_f}{\partial i_f} & \frac{\partial L_f^0 i_f}{\partial \varphi_D} & \frac{\partial L_f^0 i_f}{\partial i_q} & \frac{\partial L_f^0 i_f}{\partial \varphi_Q} & \frac{\partial L_f^0 i_f}{\partial \omega} \\ \frac{\partial L_f^0 i_q}{\partial i_d} & \frac{\partial L_f^0 i_q}{\partial i_f} & \frac{\partial L_f^0 i_q}{\partial \varphi_D} & \frac{\partial L_f^0 i_q}{\partial i_q} & \frac{\partial L_f^0 i_q}{\partial \varphi_Q} & \frac{\partial L_f^0 i_q}{\partial \omega} \\ \frac{\partial L_f^0 \omega}{\partial i_d} & \frac{\partial L_f^0 \omega}{\partial i_f} & \frac{\partial L_f^0 \omega}{\partial \varphi_D} & \frac{\partial L_f^0 \omega}{\partial i_q} & \frac{\partial L_f^0 \omega}{\partial \varphi_Q} & \frac{\partial L_f^0 \omega}{\partial \omega} \\ \frac{\partial L_f^1 i_d}{\partial i_d} & \frac{\partial L_f^1 i_d}{\partial i_f} & \frac{\partial L_f^1 i_d}{\partial \varphi_D} & \frac{\partial L_f^1 i_d}{\partial i_q} & \frac{\partial L_f^1 i_d}{\partial \varphi_Q} & \frac{\partial L_f^1 i_d}{\partial \omega} \\ \frac{\partial L_f^1 i_q}{\partial i_d} & \frac{\partial L_f^1 i_q}{\partial i_f} & \frac{\partial L_f^1 i_q}{\partial \varphi_D} & \frac{\partial L_f^1 i_q}{\partial i_q} & \frac{\partial L_f^1 i_q}{\partial \varphi_Q} & \frac{\partial L_f^1 i_q}{\partial \omega} \end{bmatrix} \tag{8}$$

After each matrix member of Eq. (8) is calculated [8], its determinant calculation gives:

$$\begin{aligned} Det(O_2) = &-\frac{\omega^2 L_{md}\left(-L_D{}^2 L_f L_{mq} + L_D L_{md}{}^2 L_{mq}\right)}{L_D{}^2\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)\left(-L_{mq}{}^2 + L_q L_Q\right)} - \\ &-\frac{L_{mq} R_Q\left(-L_f L_{md} L_Q R_D + L_{md}{}^2 L_Q R_D\right)}{L_D L_Q{}^2\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)\left(-L_{mq}{}^2 + L_q L_Q\right)} \end{aligned} \tag{9}$$

While observing both determinants (Eqs. (7) and (9)):

$Det\ O_1 \neq 0$, for $\omega \neq 0$, while $Det\ O_2 \neq 0$, for $\omega = 0$ it is easy to see that:

$Det\ (O_1) \neq 0\ U\ Det\ (O_2) \neq 0 => rank\ \{O\} = 6$.

Matrix O is full rank matrix and it could be concluded that the system is weakly locally observable.

To make a proof of observer Eq. (5) stability, Lyapunov function Eq. (10) is proposed:

$$V_1 = \frac{e_1^2}{2} + \frac{e_2^2}{2} + \frac{e_3^2}{2} + \frac{e_4^2}{2} + \frac{e_5^2}{2} + \frac{e_6^2}{2} \tag{10}$$

Equation (10) is positive definite function of the error variables: e_1, e_2, e_3, e_4, e_5, e_6. Error dynamic system is obtained by Eqs. (4) and (5), and the result is:

$$\begin{bmatrix} \dot{e_1} \\ \dot{e_2} \\ \dot{e_3} \\ \dot{e_4} \\ \dot{e_5} \\ \dot{e_6} \end{bmatrix} = \begin{bmatrix} a_4e_3 + a_5\omega e_5 - k_{11}e_1 \\ b_4e_3 + b_5\omega e_5 - k_{22}e_1 \\ c_3e_3 - k_{31}e_1 - k_{32}e_2 + k_{33}e_4 + k_{34}e_6 \\ d_4\omega e_3 + d_5e_5 - k_{43}e_4 \\ f_2e_5 - k_{51}e_1 - k_{52}e_2 - k_{53}e_4 - k_{54}e_6 \\ g_3i_qe_3 + g_4i_de_5 - k_{64}e_6 \end{bmatrix} \tag{11}$$

Then, derivation of the Lyapunov function Eq. (10) is done. Using substitution of the Eq. (11), the results is:

$$\begin{aligned} \dot{V_1} = {} & a_4e_1e_3 + a_5\omega e_1e_5 - k_{11}e_1^2 + b_4e_2e_3 + b_5\omega e_2e_5 - k_{22}e_2^2 + \\ & + c_3e_3^2 - k_{31}e_1e_3 - k_{32}e_2e_3 - k_{33}e_3e_4 - k_{34}e_3e_6 + d_4\omega e_3e_4 + \\ & + d_5e_4e_5 - k_{43}e_4^2 + + f_2e_5^2 - k_{51}e_1e_5 - k_{52}e_2e_5 - k_{53}e_4e_5 \\ & - k_{54}e_5e_6 + + g_3i_qe_3e_6 + g_4i_de_5e_6 - k_{64}e_6^2 \end{aligned} \tag{12}$$

If the coefficients k_{xy} are defined as stated:

$$k_{31} = a_4; k_{32} = b_4; k_{33} = d_4\omega; k_{34} = g_3i_q; k_{51} = a_5\omega; k_{52} = b_5\omega;$$
$$k_{53} = d_5; k_{54} = g_4i_d; k_{11}, k_{22}, k_{43}, k_{64} > 0$$

Derivation of the Lyapunov function becomes:

$$\dot{V}_1 = -k_{11}e_1^2 - k_{22}e_2^2 + c_3e_3^2 - k_{43}e_4^2 + f_2e_5^2 - k_{64}e_6^2 \tag{13}$$

Due to the character of the damper winding, the parameters c_3 and f_2 are negative for each SM. That is why it is easy to make Eq. (13) to be negative definite. When $\dot{V}_1 < 0$ is achieved, a global asymptotic stability of the observer is proved.

2.3 Damper winding reduced order flux observer

To obtain full order observer it is necessary for the stator and rotor voltages to be known. Knowledge of the load torque is also needed. Therefore, simpler observer has been found reference [10]. If the stator and rotor current dynamics equations from the dynamic system Eq. (4) are omitted, reduced order observer could be defined:

$$\begin{bmatrix} \dot{\widehat{\psi_D}} \\ \dot{\widehat{\psi_Q}} \\ \dot{\widehat{\omega}} \end{bmatrix} = \begin{bmatrix} c_1i_d + c_2i_f + c_3\widehat{\psi_D} + k_{31}e_6 \\ f_1i_q + f_2\widehat{\psi_Q} + k_{51}e_6 \\ g_1i_di_q + g_2i_fi_q + g_3i_q\widehat{\psi_D} + g_4i_d\widehat{\psi_Q} + g_5T_L + k_{61}e_6 \end{bmatrix} \tag{14}$$

It is easy to see that to obtain an observer Eq. (14) it is not needed to know the stator and rotor voltages.

Stability can be proved by the following Lyapunov function:

$$V = \frac{e_3^2}{2} + \frac{e_5^2}{2} + \frac{e_6^2}{2} \tag{15}$$

Error dynamics are obtained in similar way as for the full order observer. If the coefficients k_{xy} are defined as stated: $k_{31} = g_3\, i_q$, $k_{51} = g_4\, i_d$, $k_{61} > 0$, derivation of the Lyapunov function is negative definite and stability of the observer is proved:

$$\dot{V} = c_3 e_3^2 + f_2 e_5^2 - k_{61} e_6^2 \tag{16}$$

If the motion dynamics equation from the dynamic system is omitted, the simplest observer can be defined:

$$\begin{bmatrix} \dot{\widehat{\psi_D}} \\ \dot{\widehat{\psi_Q}} \end{bmatrix} = \begin{bmatrix} c_1 i_d + c_2 i_f + c_3 \widehat{\psi_D} \\ f_1 i_q + f_2 \widehat{\psi_Q} \end{bmatrix} \tag{17}$$

This observer includes only damper winding dynamic equations, and for its operation only rotor and stator current components are needed.

Stability can be proved in the same way as for the previous observers. If a positive definite Lyapunov function Eq. (18) is considered:

$$V = \frac{e_3^2}{2} + \frac{e_5^2}{2} \tag{18}$$

It has negative definite derivation Eq. (19) and stability is proved.

$$\dot{V} = c_3 e_3^2 + f_2 e_5^2 \tag{19}$$

2.4 Damper winding flux observer with adaptation of resistance

Full order observer can be also used for the adaptation of the stator and rotor resistances. Firstly, dynamic system Eq. (4) has to be expanded:

$$\begin{bmatrix} \dot{i_d} \\ \dot{i_f} \\ \dot{\psi_D} \\ \dot{i_q} \\ \dot{\psi_Q} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} a_1 i_d + a_2 i_f + a_3 i_q \omega + a_4 \psi_D + a_5 \psi_Q \omega + a_6 i_f R_f + a_7 i_d R_S + a_8 u_d + a_9 u_f \\ b_1 i_d + b_2 i_f + b_3 i_q \omega + b_4 \psi_D + b_5 \psi_Q \omega + b_6 i_f R_f + b_7 i_d R_S + b_8 u_d + b_9 u_f \\ c_1 i_d + c_2 i_f + c_3 \psi_D \\ d_1 i_q + d_2 i_d \omega + d_3 i_f \omega + d_4 \omega \psi_D + d_5 \psi_Q + d_6 i_q R_S + d_7 u_q \\ f_1 i_q + f_2 \psi_Q \\ g_1 i_d i_q + g_2 i_f i_q + g_3 i_q \psi_D + g_4 i_d \psi_Q + g_5 M_T \end{bmatrix} \tag{20}$$

In a similar way as for the full order observer Eq. (5), an observer for adaptation could be defined:

$$\begin{bmatrix} \dot{\widehat{i_d}} \\ \dot{\widehat{i_f}} \\ \dot{\widehat{\psi_D}} \\ \dot{\widehat{i_q}} \\ \dot{\widehat{\psi_Q}} \\ \dot{\widehat{\omega}} \end{bmatrix} = \begin{bmatrix} a_1 i_d + a_2 i_f + a_3 i_q \omega + a_4 \widehat{\psi_D} + a_5 \widehat{\psi_Q} \omega + a_6 i_f \widehat{R}_f + a_7 i_d \widehat{R}_s + a_8 u_d + a_9 u_f + k_{11} e_1 \\ b_1 i_d + b_2 i_f + b_3 i_q \omega + b_4 \widehat{\psi_D} + b_5 \widehat{\psi_Q} \omega + b_6 i_f \widehat{R}_f + b_7 i_d \widehat{R}_s + b_8 u_d + b_9 u_f + k_{22} e_2 \\ c_1 i_d + c_2 i_f + c_3 \widehat{\psi_D} + k_{31} e_1 + k_{32} e_2 + k_{33} e_4 + k_{34} e_6 \\ d_1 i_q + d_2 i_d \omega + d_3 i_f \omega + d_4 \omega \widehat{\psi_D} + d_5 \widehat{\psi_Q} + d_6 i_q \widehat{R}_s + d_7 u_q + k_{43} e_4 \\ f_1 i_q + f_2 \widehat{\psi_Q} + k_{51} e_1 + k_{52} e_2 + k_{53} e_4 + k_{54} e_6 \\ g_1 i_d i_q + g_2 i_f i_q + g_3 i_q \widehat{\psi_D} + g_4 i_d \widehat{\psi_Q} + g_5 M_T + k_{64} e_6 \end{bmatrix} \tag{21}$$

Its error dynamics Eqs. (20) and (21) are obtained:

$$\begin{bmatrix} \dot{e_1} \\ \dot{e_2} \\ \dot{e_3} \\ \dot{e_4} \\ \dot{e_5} \\ \dot{e_6} \end{bmatrix} = \begin{bmatrix} a_4e_3 + a_5\omega e_5 + a_6 i_f \Delta R_f + a_7 i_d \Delta R_s - k_{11}e_1 \\ b_4e_3 + b_5\omega e_5 + b_6 i_f \Delta R_f + b_7 i_d \Delta R_s - k_{22}e_1 \\ c_3e_3 - k_{31}e_1 - k_{32}e_2 + k_{33}e_4 + k_{34}e_6 \\ d_4\omega e_3 + d_5e_5 + d_6 i_q \Delta R_s - k_{43}e_4 \\ f_2e_5 - k_{51}e_1 - k_{52}e_2 - k_{53}e_4 - k_{54}e_6 \\ g_3 i_q e_3 + g_4 i_d e_5 - k_{64}e_6 \end{bmatrix} \tag{22}$$

For the positive definite Lyapunov function:

$$V_1 = \frac{e_1^2}{2} + \frac{e_2^2}{2} + \frac{e_3^2}{2} + \frac{e_4^2}{2} + \frac{e_5^2}{2} + \frac{e_6^2}{2} + \frac{\Delta R_f^2}{2} + \frac{\Delta R_s^2}{2} \tag{23}$$

under the assumption that the changes of the rotor and stator resistances are much slower than the changes of electromagnetic states, derivation of the Eq. (23) is:

$$\begin{aligned} \dot{V_1} = {} & a_4e_1e_3 + a_5\omega e_1e_5 + a_6 i_f e_1 \Delta R_f + a_7 i_d e_1 \Delta R_s - k_{11}e_1^2 + b_4e_2e_3 + b_5\omega e_2e_5 + \\ & + b_6 i_f e_2 \Delta R_f + b_7 i_d e_1 \Delta R_s - k_{22}e_2^2 + c_3e_3^2 - k_{31}e_1e_3 - k_{32}e_2e_3 - k_{33}e_3e_4 \\ & - k_{34}e_3e_6 + d_4\omega e_3e_4 + d_5e_4e_5 + d_6 i_q e_4 \Delta R_s - k_{43}e_4^2 + f_2e_5^2 - k_{51}e_1e_5 \\ & - k_{52}e_2e_5 - k_{53}e_4e_5 - -k_{54}e_5e_6 + g_3 i_q e_3e_4 + g_4 i_d e_5e_6 - k_{64}e_6^2 - \Delta R_s \dot{\widehat{R_s}} - \Delta R_f \dot{\widehat{R_f}} \end{aligned} \tag{24}$$

If the rules for resistance adaptation are given as stated:

$$\dot{\widehat{R_f}} = a_6 i_f e_1 + b_6 i_f e_2 \tag{25}$$

$$\dot{\widehat{R_s}} = a_7 i_d e_1 + b_7 i_d e_2 + d_6 i_q e_4 \tag{26}$$

Derivation of the Lyapunov function in Eq. (24) becomes the same as the one given in Eq. (12), and stability of the observer Eq. (21) is proved.

2.5 Load torque estimation

To accomplish the SM speed tracking control, except from damper winding observer, load torque estimation is also necessary to be done. SM dynamic system given in Eq. (4) is expended with more state variables. One of them is rotor angle (γ) which is measured state variable. Another is load torque (T_L) that is not measured. Although load torque dynamic is not known, according to reference [11] it could be added as a state variable with the first derivation equal to zero. Expended dynamic system is:

$$\begin{bmatrix} \dot{i_d} \\ \dot{i_f} \\ \dot{\psi_D} \\ \dot{i_q} \\ \dot{\psi_Q} \\ \dot{\omega} \\ \dot{\gamma} \\ \dot{T_L} \end{bmatrix} = \begin{bmatrix} a_1i_d + a_2i_f + a_3i_q\omega + a_4\psi_D + a_5\psi_Q\omega + a_6u_d + a_7u_f \\ b_1i_d + b_2i_f + b_3i_q\omega + b_4\psi_D + b_5\psi_Q\omega + b_6u_d + b_7u_f \\ c_1i_d + c_2i_f + c_3\psi_D \\ d_1i_q + d_2i_d\omega + d_3i_f\omega + d_4\omega\psi_D + d_5\psi_Q + d_6u_q \\ f_1i_q + f_2\psi_Q \\ g_1i_di_q + g_2i_fi_q + g_3i_q\psi_D + g_4i_d\psi_Q + g_5T_L \\ \omega \\ 0 \end{bmatrix} \tag{27}$$

Observability analysis of the Eq. (27) is obtained according to the nonlinear system weak observability concept [9]. Observability criterion matrix O_1 (28) has been chosen:

$$O_1 = \begin{bmatrix} di_d \\ di_f \\ di_q \\ d\gamma \\ d(L_f i_d) \\ d(L_f i_q) \\ d(L_f \gamma) \\ d\left(L_f^2 \gamma\right) \end{bmatrix} = \begin{bmatrix}
\frac{\partial L_f^0 i_d}{\partial i_d} & \frac{\partial L_f^0 i_d}{\partial i_f} & \frac{\partial L_f^0 i_d}{\partial \varphi_D} & \frac{\partial L_f^0 i_d}{\partial i_q} & \frac{\partial L_f^0 i_d}{\partial \varphi_Q} & \frac{\partial L_f^0 i_d}{\partial \omega} & \frac{\partial L_f^0 i_d}{\partial \gamma} & \frac{\partial L_f^0 i_d}{\partial T_L} \\
\frac{\partial L_f^0 i_f}{\partial i_d} & \frac{\partial L_f^0 i_f}{\partial i_f} & \frac{\partial L_f^0 i_f}{\partial \varphi_D} & \frac{\partial L_f^0 i_f}{\partial i_q} & \frac{\partial L_f^0 i_f}{\partial \varphi_Q} & \frac{\partial L_f^0 i_f}{\partial \omega} & \frac{\partial L_f^0 i_f}{\partial \gamma} & \frac{\partial L_f^0 i_f}{\partial T_L} \\
\frac{\partial L_f^0 i_q}{\partial i_d} & \frac{\partial L_f^0 i_q}{\partial i_f} & \frac{\partial L_f^0 i_q}{\partial \varphi_D} & \frac{\partial L_f^0 i_q}{\partial i_q} & \frac{\partial L_f^0 i_q}{\partial \varphi_Q} & \frac{\partial L_f^0 i_q}{\partial \omega} & \frac{\partial L_f^0 i_q}{\partial \gamma} & \frac{\partial L_f^0 i_q}{\partial T_L} \\
\frac{\partial L_f^0 \gamma}{\partial i_d} & \frac{\partial L_f^0 \gamma}{\partial i_f} & \frac{\partial L_f^0 \gamma}{\partial \varphi_D} & \frac{\partial L_f^0 \gamma}{\partial i_q} & \frac{\partial L_f^0 \gamma}{\partial \varphi_Q} & \frac{\partial L_f^0 \gamma}{\partial \omega} & \frac{\partial L_f^0 \gamma}{\partial \gamma} & \frac{\partial L_f^0 \gamma}{\partial T_L} \\
\frac{\partial L_f^1 i_d}{\partial i_d} & \frac{\partial L_f^1 i_d}{\partial i_f} & \frac{\partial L_f^1 i_d}{\partial \varphi_D} & \frac{\partial L_f^1 i_d}{\partial i_q} & \frac{\partial L_f^1 i_d}{\partial \varphi_Q} & \frac{\partial L_f^1 i_d}{\partial \omega} & \frac{\partial L_f^1 i_d}{\partial \gamma} & \frac{\partial L_f^1 i_d}{\partial T_L} \\
\frac{\partial L_f^1 i_q}{\partial i_d} & \frac{\partial L_f^1 i_q}{\partial i_f} & \frac{\partial L_f^1 i_q}{\partial \varphi_D} & \frac{\partial L_f^1 i_q}{\partial i_q} & \frac{\partial L_f^1 i_q}{\partial \varphi_Q} & \frac{\partial L_f^1 i_q}{\partial \omega} & \frac{\partial L_f^0 i_q}{\partial \gamma} & \frac{\partial L_f^0 i_q}{\partial T_L} \\
\frac{\partial L_f^1 \gamma}{\partial i_d} & \frac{\partial L_f^1 \gamma}{\partial i_f} & \frac{\partial L_f^1 \gamma}{\partial \varphi_D} & \frac{\partial L_f^1 \gamma}{\partial i_q} & \frac{\partial L_f^1 \gamma}{\partial \varphi_Q} & \frac{\partial L_f^1 \gamma}{\partial \omega} & \frac{\partial L_f^0 \gamma}{\partial \gamma} & \frac{\partial L_f^0 \gamma}{\partial T_L} \\
\frac{\partial L_f^2 \gamma}{\partial i_d} & \frac{\partial L_f^2 \gamma}{\partial i_f} & \frac{\partial L_f^2 \gamma}{\partial \varphi_D} & \frac{\partial L_f^2 \gamma}{\partial i_q} & \frac{\partial L_f^2 \gamma}{\partial \varphi_Q} & \frac{\partial L_f^2 \gamma}{\partial \omega} & \frac{\partial L_f^2 \gamma}{\partial \gamma} & \frac{\partial L_f^2 \gamma}{\partial T_L}
\end{bmatrix} \tag{28}$$

After each matrix member of Eq. (28) is calculated [8], its determinant calculation gives:

$$\begin{aligned} Det(O_1) = &-\frac{\omega^2 L_{md} L_Q \left(-L_D L_f L_{mq} + {L_{md}}^2 L_{mq}\right)}{2HL_D L_Q \left(-L_d L_D L_f + L_d {L_{md}}^2 + L_D {L_{md}}^2 + L_f {L_{md}}^2 - 2{L_{md}}^3\right)\left(-{L_{mq}}^2 + L_q L_Q\right)} \\ &-\frac{L_{mq} R_Q \left(-L_f L_{md} R_D + {L_{md}}^2 R_D\right)}{2HL_D L_Q \left(-L_d L_D L_f + L_d {L_{md}}^2 + L_D {L_{md}}^2 + L_f {L_{md}}^2 - 2{L_{md}}^3\right)\left(-{L_{mq}}^2 + L_q L_Q\right)} \end{aligned} \tag{29}$$

Observability criterion matrix O_2 has been chosen:

$$O_2 = \begin{bmatrix} di_d \\ di_f \\ di_q \\ d\gamma \\ d(L_f i_d) \\ d(L_f i_f) \\ d(L_f \gamma) \\ d\left(L_f^2 \gamma\right) \end{bmatrix} = \begin{bmatrix}
\frac{\partial L_f^0 i_d}{\partial i_d} & \frac{\partial L_f^0 i_d}{\partial i_f} & \frac{\partial L_f^0 i_d}{\partial \varphi_D} & \frac{\partial L_f^0 i_d}{\partial i_q} & \frac{\partial L_f^0 i_d}{\partial \varphi_Q} & \frac{\partial L_f^0 i_d}{\partial \omega} & \frac{\partial L_f^0 i_d}{\partial \gamma} & \frac{\partial L_f^0 i_d}{\partial T_L} \\
\frac{\partial L_f^0 i_f}{\partial i_d} & \frac{\partial L_f^0 i_f}{\partial i_f} & \frac{\partial L_f^0 i_f}{\partial \varphi_D} & \frac{\partial L_f^0 i_f}{\partial i_q} & \frac{\partial L_f^0 i_f}{\partial \varphi_Q} & \frac{\partial L_f^0 i_f}{\partial \omega} & \frac{\partial L_f^0 i_f}{\partial \gamma} & \frac{\partial L_f^0 i_f}{\partial T_L} \\
\frac{\partial L_f^0 i_q}{\partial i_d} & \frac{\partial L_f^0 i_q}{\partial i_f} & \frac{\partial L_f^0 i_q}{\partial \varphi_D} & \frac{\partial L_f^0 i_q}{\partial i_q} & \frac{\partial L_f^0 i_q}{\partial \varphi_Q} & \frac{\partial L_f^0 i_q}{\partial \omega} & \frac{\partial L_f^0 i_q}{\partial \gamma} & \frac{\partial L_f^0 i_q}{\partial T_L} \\
\frac{\partial L_f^0 \gamma}{\partial i_d} & \frac{\partial L_f^0 \gamma}{\partial i_f} & \frac{\partial L_f^0 \gamma}{\partial \varphi_D} & \frac{\partial L_f^0 \gamma}{\partial i_q} & \frac{\partial L_f^0 \gamma}{\partial \varphi_Q} & \frac{\partial L_f^0 \gamma}{\partial \omega} & \frac{\partial L_f^0 \gamma}{\partial \gamma} & \frac{\partial L_f^0 \gamma}{\partial T_L} \\
\frac{\partial L_f^1 i_d}{\partial i_d} & \frac{\partial L_f^1 i_d}{\partial i_f} & \frac{\partial L_f^1 i_d}{\partial \varphi_D} & \frac{\partial L_f^1 i_d}{\partial i_q} & \frac{\partial L_f^1 i_d}{\partial \varphi_Q} & \frac{\partial L_f^1 i_d}{\partial \omega} & \frac{\partial L_f^1 i_d}{\partial \gamma} & \frac{\partial L_f^1 i_d}{\partial T_L} \\
\frac{\partial L_f^1 i_f}{\partial i_d} & \frac{\partial L_f^1 i_f}{\partial i_f} & \frac{\partial L_f^1 i_f}{\partial \varphi_D} & \frac{\partial L_f^1 i_f}{\partial i_q} & \frac{\partial L_f^1 i_f}{\partial \varphi_Q} & \frac{\partial L_f^1 i_f}{\partial \omega} & \frac{\partial L_f^0 i_f}{\partial \gamma} & \frac{\partial L_f^0 i_f}{\partial T_L} \\
\frac{\partial L_f^1 \gamma}{\partial i_d} & \frac{\partial L_f^1 \gamma}{\partial i_f} & \frac{\partial L_f^1 \gamma}{\partial \varphi_D} & \frac{\partial L_f^1 \gamma}{\partial i_q} & \frac{\partial L_f^1 \gamma}{\partial \varphi_Q} & \frac{\partial L_f^1 \gamma}{\partial \omega} & \frac{\partial L_f^0 \gamma}{\partial \gamma} & \frac{\partial L_f^0 \gamma}{\partial T_L} \\
\frac{\partial L_f^2 \gamma}{\partial i_d} & \frac{\partial L_f^2 \gamma}{\partial i_f} & \frac{\partial L_f^2 \gamma}{\partial \varphi_D} & \frac{\partial L_f^2 \gamma}{\partial i_q} & \frac{\partial L_f^2 \gamma}{\partial \varphi_Q} & \frac{\partial L_f^2 \gamma}{\partial \omega} & \frac{\partial L_f^2 \gamma}{\partial \gamma} & \frac{\partial L_f^2 \gamma}{\partial T_L}
\end{bmatrix} \tag{30}$$

After each matrix member of Eq. (30) is calculated [8], its determinant calculation gives:

$$Det(O_2) = \frac{\omega L_{md} L_{mq} R_D}{2HL_D L_Q\left(-L_d L_D L_f + L_d L_{md}{}^2 + L_D L_{md}{}^2 + L_f L_{md}{}^2 - 2L_{md}{}^3\right)} \tag{31}$$

While observing both Eqs. (29) and (31):

$$Det\ O_1 \neq 0, \text{for } \omega = 0, \text{while } Det\ O_2 \neq 0, \text{for } \omega \neq 0$$

It is easy to see that: $Det\ (O_1) \neq 0\ U\ Det\ (O_2) \neq 0$ = > *rank* $\{O\}$ = 8.

Matrix O is full rank matrix and it could be concluded that the system in Eq. (27) is weakly locally observable. After it is concluded that the system is observable, a load torque estimator has to be made.

Using comparison between measured and calculated rotor speed values, a model reference adaptive system (MRAS) has been made.

Starting from the system that includes only rotor angle and rotor speed dynamics Eq. (32), the stability analysis of the proposed MRAS estimation has been made.

$$\begin{bmatrix} \dot{\gamma} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \omega \\ g_5 T_L + \frac{1}{2H} T_e \end{bmatrix} \tag{32}$$

where *Te* states for electromagnetic torque.

Then, an observer is proposed:

$$\begin{bmatrix} \dot{\widehat{\gamma}} \\ \dot{\widehat{\omega}} \end{bmatrix} = \begin{bmatrix} \widehat{\omega} \\ g_5 \widehat{T_L} + \frac{1}{2H} T_e \end{bmatrix} \tag{33}$$

Both, reference Eq. (32) and observed Eq. (33) systems can be noted in the form of linear systems as is given respectively in Eqs. (34) and (35):

$$[\dot{X}] = [\mathrm{A}][X] + [\mathrm{B}][U] + [\mathrm{D}]; \tag{34}$$

$$\left[\dot{\widehat{X}}\right] = [\mathrm{A}]\left[\widehat{X}\right] + [\mathrm{B}][U] + \left[\widehat{\mathrm{D}}\right]; \tag{35}$$

where:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}; \quad \mathrm{BU} = \begin{bmatrix} 0 \\ \frac{1}{2H} T_e \end{bmatrix}; \quad D = \begin{bmatrix} 0 \\ g_5 T_{L.} \end{bmatrix}$$

Error dynamics is obtained by Eqs. (34) and (35):

$$[\dot{\varepsilon}] = [\mathrm{A}][\varepsilon] - [\mathrm{W}] \tag{36}$$

where:

$$\varepsilon = \begin{bmatrix} \varepsilon_\gamma \\ \varepsilon_\omega \end{bmatrix} = \begin{bmatrix} \gamma - \widehat{\gamma} \\ \omega - \widehat{\omega} \end{bmatrix}; \quad W = \begin{bmatrix} 0 \\ g_5 \end{bmatrix}\left(T_L - \widehat{T_L}\right)$$

Expression in Eq. (36) can be noted as:

$$\begin{bmatrix} \dot{\varepsilon_\gamma} \\ \dot{\varepsilon_\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \varepsilon_\gamma \\ \varepsilon_\omega \end{bmatrix} - \begin{bmatrix} 0 \\ g_5\left(T_L - \widehat{T_L}\right) \end{bmatrix} \tag{37}$$

According to the Popov stability criterion, stability will be proved by achieving the condition:

$$\int_0^t [\varepsilon]^T [\mathrm{W}] dt \geq -\gamma_0^2 \tag{38}$$

when $t \geq 0, \gamma_0 \geq 0$.

With further expansion of the Eq. (38), stability condition becomes:

$$\int_0^t [\varepsilon_\gamma \varepsilon_\omega] \begin{bmatrix} 0 \\ g_5\left(T_L - \widehat{T_L}\right) \end{bmatrix} \geq -\gamma_0^2 \tag{39}$$

$$\int_0^t \varepsilon_\omega g_5\left(T_L - \widehat{T_L}\right) \geq -\gamma_0^2 \tag{40}$$

According to the literature reference [12] it is obvious that inequality Eq. (40) is satisfied if:

$$\widehat{\mathrm{T}_L} = \widehat{\mathrm{T}_L}(0) + k_p\left[\varepsilon_\omega \frac{1}{2H}\right] + k_i \int_0^t \left[\varepsilon_\omega \frac{1}{2H}\right] dt \tag{41}$$

According to [12] stability of the load torque estimation Eq. (41) is achieved for each positive value of the proportional k_p and integral k_i coefficients.

3. Control law

Nonlinear control system is made by feedback linearization technique. It is not possible to obtain exact linearization for the SM system, so partial input output linearization has been applied. Using Lie algebra, the decoupled control system has been made. Control demand is to make a tracking of two outputs: rotor speed, and square of stator magnetic flux: $\widehat{\omega}, \widehat{\psi}_s^2 = \widehat{\psi}_d^2 + \widehat{\psi}_q^2$.

According to the feedback linearization technique, output should be derived until in its expressions an input variable appears.

After the first derivation of the rotor speed Eq. (42), output variable has not appeared.

$$\dot{\widehat{\omega}} = \mathrm{g}_1 i_d i_q + g_2 i_f i_q + g_3 i_q \widehat{\varphi_D} + g_4 i_d \widehat{\varphi_Q} + g_5 T_L + k_{64} e_6 \tag{42}$$

Equation (42) could be noted as:

$$\dot{\widehat{\omega}} = \widehat{h}_{11} + g_5 T_L + \Delta \tag{43}$$

where:

$$\widehat{\mathrm{h}}_{11} = \mathrm{g}_1 i_d i_q + g_2 i_f i_q + g_3 i_q \widehat{\varphi_D} + g_4 i_d \widehat{\varphi_Q} \tag{44}$$

$$\Delta = k_{64}e_4 \tag{45}$$

Since the output variable has not appeared yet, derivation of the additional output variable h_{11} has been done. After the derivation of h_{11}, that is actually an electromagnetic torque, output variables appear. Derivation of h_{11} is given in Eq. (46), and derivation of the second output variable in Eq. (47).

$$\dot{\widehat{h}}_{11} = L_{\hat{f}}\widehat{h}_{11} + L_{g1}\widehat{h}_{11}u_d + L_{g2}\widehat{h}_{11}u_q \tag{46}$$

$$\dot{\widehat{\psi_s^2}} = L_{\hat{f}}\widehat{\psi_s^2} + L_{g1}\widehat{\psi_s^2}u_d + L_{g2}\widehat{\psi_s^2}u_q \tag{47}$$

Dynamical system of the output variables is:

$$\begin{bmatrix} \dot{\widehat{\omega}} \\ \dot{\widehat{h}}_{11} \\ \dot{\widehat{\psi_s^2}} \end{bmatrix} = \begin{bmatrix} \widehat{h}_{11} + g_5 T_L + \Delta \\ L_{\hat{f}}\widehat{h}_{11} + L_{g1}\widehat{h}_{11}u_d + L_{g2}\widehat{h}_{11}u_q \\ L_{\hat{f}}\widehat{\psi_s^2} + L_{g1}\widehat{\psi_s^2}u_d + L_{g2}\widehat{\psi_s^2}u_q \end{bmatrix} \tag{48}$$

It is possible to obtain the control of the last two variables, as stated:

$$\begin{bmatrix} \dot{\widehat{h}}_{11} \\ \dot{\widehat{\psi_s^2}} \end{bmatrix} = \begin{bmatrix} L_{\hat{f}}\widehat{h}_{11} \\ L_{\hat{f}}\widehat{\psi_s^2} \end{bmatrix} + G\begin{bmatrix} u_d \\ u_q \end{bmatrix} \tag{49}$$

where G is decoupling matrix:

$$G = \begin{bmatrix} L_{g1}\widehat{h}_{11} & L_{g2}\widehat{h}_{11} \\ L_{g1}\widehat{\psi_s^2} & L_{g2}\widehat{\psi_s^2} \end{bmatrix} \tag{50}$$

Now it is possible to define the control law:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = G^{-1}\begin{bmatrix} -L_{\hat{f}}\widehat{h}_{11} - k_{p1}e_8 + \dot{h}_{11ref} - e_7 \\ -L_{\hat{f}}\widehat{\psi_s^2} - k_{p2}e_9 + \dot{\psi}_{sref}^2 \end{bmatrix} \tag{51}$$

where difference form the reference values are:

$$e_7 = \widehat{\omega} - \omega_{ref};\ e_8 = \widehat{h}_{11} - h_{11ref};\quad e_9 = \widehat{\psi_s^2} - \psi_{sref}^2$$

If h_{11ref} is defined given:

$$h_{11ref} = \dot{\omega}_{ref} - g_5 T_L - k_{p0}e_7 - \Delta \tag{52}$$

Using (51) and (52), further expansion of Eq. (49) gives:

$$\begin{bmatrix} \dot{\widehat{h}}_{11} \\ \dot{\widehat{\psi_s^2}} \end{bmatrix} = \begin{bmatrix} L_{\hat{f}}\widehat{h}_{11} \\ L_{\hat{f}}\widehat{\psi_s^2} \end{bmatrix} + GG^{-1}\begin{bmatrix} -L_{\hat{f}}\widehat{h}_{11} - k_{p1}e_8 + \dot{h}_{11ref} - e_7 \\ -L_{\hat{f}}\widehat{\psi_s^2} - k_{p2}e_9 + \dot{\psi}_{sref}^2 \end{bmatrix} \tag{53}$$

$$\begin{bmatrix} \dot{\widehat{h}}_{11} \\ \dot{\widehat{\psi_s^2}} \end{bmatrix} = \begin{bmatrix} L_{\hat{f}}\widehat{h}_{11} - L_{\hat{f}}\widehat{h}_{11} - k_{p1}e_8 + \dot{h}_{11ref} - e_7 \\ L_{\hat{f}}\widehat{\psi_s^2} - L_{\hat{f}}\widehat{\psi_s^2} - k_{p2}e_9 + \dot{\psi}_{sref}^2 \end{bmatrix} \tag{54}$$

$$\begin{bmatrix} \dot{\widehat{h_{11}}} & -\dot{h}_{11ref} \\ \dot{\widehat{\psi_s^2}} & -\dot{\psi}_{sref}^2 \end{bmatrix} = \begin{bmatrix} -k_{p1}e_8 - e_7 \\ -k_{p2}e_9 \end{bmatrix} \tag{55}$$

In Eq. (55) error dynamics of e_8 and e_9 are obtained. It is left to obtain error dynamic of the e_7. Using Eqs. (43) and (52) error dynamic of e_7 is obtained and its expression is given:

$$\dot{\omega} - \dot{\omega}_{ref} = \widehat{h}_{11} + g_5 T_L + \Delta - h_{11ref} - g_5 T_L - k_{p0}e_7 - \Delta \tag{56}$$

$$\dot{\omega} - \dot{\omega}_{ref} = e_8 - k_{p0}e_7 \tag{57}$$

Using Eqs. (55) and (57) the complete error dynamics system is obtained:

$$\begin{bmatrix} \dot{e}_7 \\ \dot{e}_8 \\ \dot{e}_9 \end{bmatrix} = \begin{bmatrix} \dot{\omega} - \dot{\omega}_{ref} \\ \dot{\widehat{h_{11}}} - \dot{h}_{11ref} \\ \dot{\widehat{\psi_s^2}} - \dot{\psi}_{sref}^2 \end{bmatrix} = \begin{bmatrix} e_8 - k_{p0}e_7 \\ -k_{p1}e_8 - e_7 \\ -k_{p2}e_9 \end{bmatrix} \tag{58}$$

From the Eq. (58) it is easily seen that convergence of the rotor speed (electromagnetic torque) is independent of convergence of the magnetic flux. It could be said that completely decoupled control system is achieved.

Stability of the control system can be proved by the following positive definite Lyapunov function:

$$V = \frac{e_7^2}{2} + \frac{e_8^2}{2} + \frac{e_9^2}{2} \tag{59}$$

Derivation of the Eq. (59) Lyapunov function is:

$$\dot{V} = e_7\dot{e}_7 + e_8\dot{e}_8 + e_9\dot{e}_9 \tag{60}$$

Using Eq. (58), derivation Eq. (60) could be expanded as given:

$$\dot{V} = e_7e_8 - k_{p0}e_7^2 - k_{p1}e_8^2 - e_7e_8 - k_{p2}e_9^2 \tag{61}$$

$$\dot{V} = -k_{p0}e_7^2 - k_{p1}e_8^2 - k_{p2}e_9^2 \tag{62}$$

If the coefficients k_{p0}, k_{p1} and k_{p2} are positive, derivation of the Lyapunov function Eq. (60) is negative definite and stability of the control law is proved.

4. Comparison of nonlinear and linear control systems

4.1 Control law for linear control system

Linear control system is based on stator field orientation control principle. It is cascaded control system with inner and outer control loops. Outer control loops are made for rotor speed and magnetic flux control, while inner control loops are made for current components control.

At first, current components control in inner loops will be defined.

If dynamics of the damper winding are neglected, equations of the SM system could be simplified. Then, the equation in the stator d-axis is:

$$u_d = R_s i_d + \frac{di_d}{dt}\left(L_d - \frac{{L_{md}}^2}{L_f}\right) + e_d \tag{63}$$

where

$$e_d = \frac{L_{md}}{L_f}\left(-i_f R_f + u_f\right) - \varphi_q \omega \tag{64}$$

If the additional variable $\widehat{u_d} = u_d - e_d$ is introduced, Eq. (63) becomes linear differential equation of the first order for the current componenti_d:

$$\widehat{u_d} = R_s i_d + \frac{di_d}{dt}\left(L_d - \frac{{L_{md}}^2}{L_f}\right) \tag{65}$$

Similar algebra could be done with the stator q-axis equation. Using additional variable $\widehat{u_q} = u_q - e_q$ and Eq. (66)

$$e_q = -\frac{L_{mq} R_Q}{L_Q} i_Q + \omega \varphi_d \tag{66}$$

a linear differential equation of the first order for the current component i_q is obtained:

$$\widehat{u_q} = R_s i_q - \frac{{L_{mq}}^2 - L_q L_Q}{L_Q}\frac{di_q}{dt} \tag{67}$$

Components e_d, e_q will be incorporated into the control system as decoupling.

When the Eqs. (65) and (67) are transformed into Laplace domain, the following transfer functions are obtained:

$$G(s) = \frac{I_{dq}(s)}{U_{dq}(s)} = \frac{\frac{1}{R_s}}{\tau_{cc,dq}\, s + 1} \tag{68}$$

where:

$$\mathrm{L_{cc,d}} = \mathrm{L_d} - \frac{{\mathrm{L_{md}}}^2}{\mathrm{L_f}}$$

$$\mathrm{L_{cc,q}} = \mathrm{L_q} - \frac{{\mathrm{L_{mq}}}^2}{\mathrm{L_Q}}$$

$$\tau_{\mathrm{cc,d}} = \frac{\mathrm{L_{cc,d}}}{\mathrm{R_s}}$$

$$\tau_{\mathrm{cc,q}} = \frac{\mathrm{L_{cc,q}}}{\mathrm{R_s}}$$

It is easy to see that Eq. (68) can be controlled in a closed loop by simple PI controller:

$$C_{PI}(s) = K_P + \frac{K_I}{s} \tag{69}$$

Tuning of the PI controllers is done according to Internal model control reference [13] (IMC) method as is given:

$$K_P = a_{cc} L_{cc,d} \tag{70}$$

$$K_i = a_{cc} R_s \tag{71}$$

where a_{cc} for the first order system is defined as:

$$a_{cc} = \frac{\ln(9)}{t_{r,cc}} \tag{72}$$

and $t_{r,cc}$ is stator current response time that is for most of the industrial applications [14] set at 5 ms.

Outer loop for speed control is then analyzed.

The transfer function of the current control closed loop $G_{cc}(s)$ is:

$$G_{cc,cl}(s) = \frac{C_{PI}(s)G(s)}{1 + C_{PI}(s)G(s)} \tag{73}$$

After some algebra Eq. (73) could written as:

$$G_{cc,cl}(s) = \frac{a_{cc}}{s + a_{cc}} \tag{74}$$

Outer control loops will be also controlled by PI controllers. In that case, the complete control loop for the rotor speed is given in **Figure 1**.

Open loop transfer function of the rotor speed control is:

$$G_{\omega,ol}(s) = \frac{K_{p\omega}(T_{i\omega}s + 1)}{T_{i\omega}s} \frac{a_{cc}}{s + a_{cc}} \frac{1}{Js} \tag{75}$$

According to the Eq. (75), stability analysis of the SM1 speed control loop has been done. In **Figure 2**, root locus diagram is given. It shows that, due to damping factor, values of $K_{p\omega}$ should not exceed 14.

According to the Bode diagram, given in **Figure 3**, the stability phase margin is almost 60 degrees for $K_{p\omega}$ higher than 10.

According to **Figure 1**, torque load could be analyzed as an input disturbance. Load sensitivity transfer function is obtained:

$$G_{dy}(s) = \frac{P(s)}{1 + P(s)C(s)} \tag{76}$$

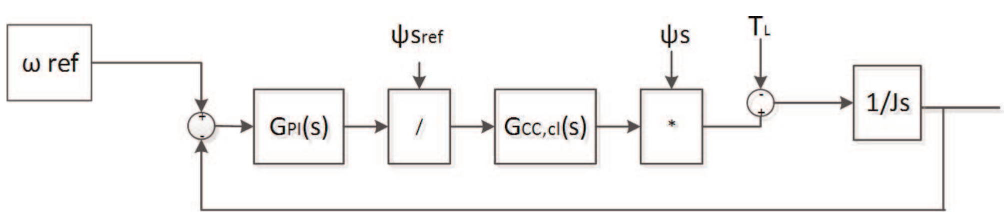

Figure 1.
Control loop of the rotor speed.

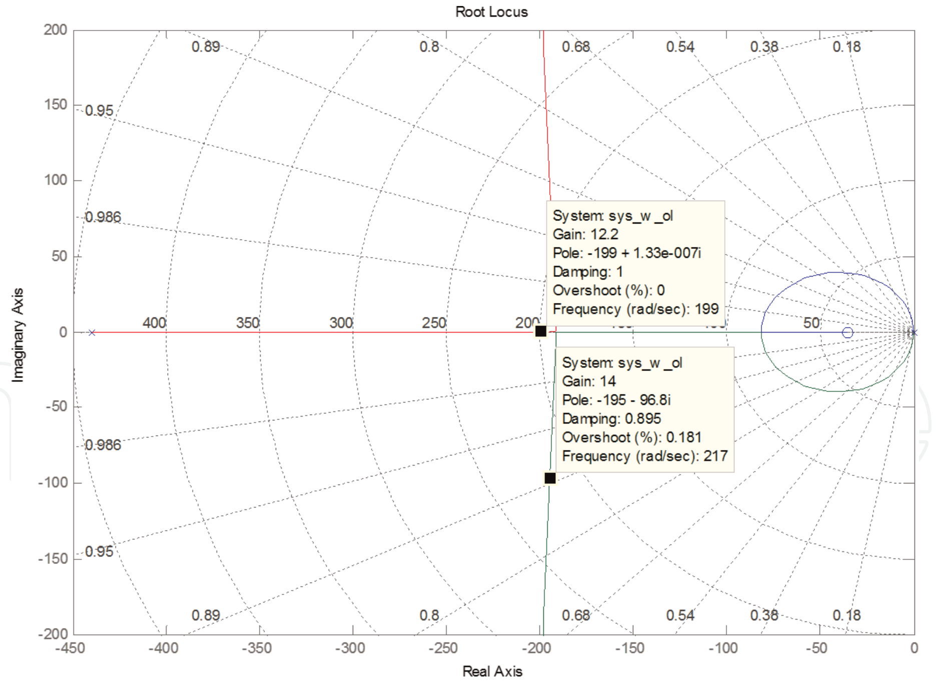

Figure 2.
Root locus for speed control.

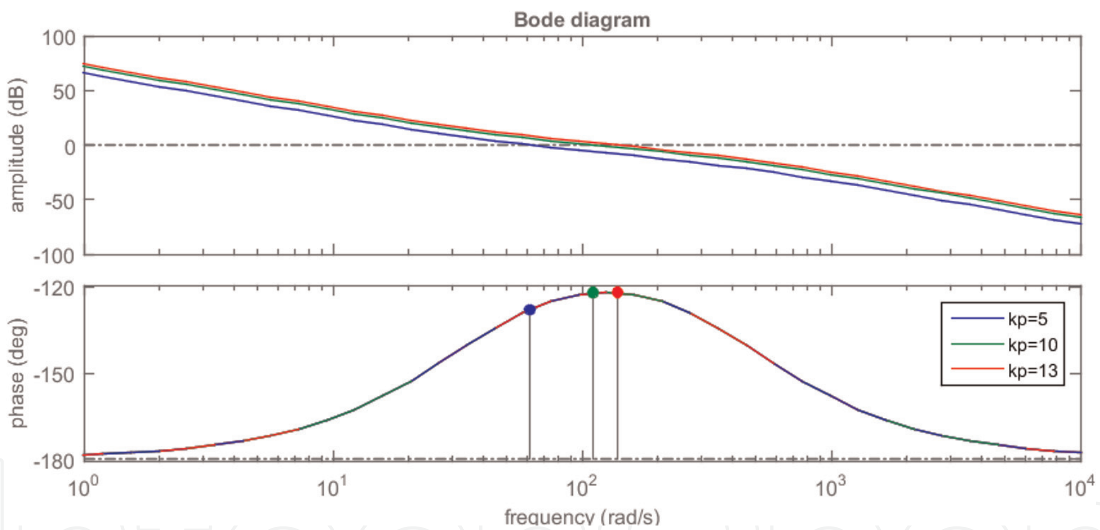

Figure 3.
Bode diagram for speed control.

where $(s) = \frac{1}{Js}$; $C(s) = \frac{K_{p\omega}(T_{i\omega}s+1)}{T_{i\omega}s}\frac{a_{cc}}{s+a_{cc}}$

Step response for the torque disturbance is given in **Figure 4**. It could be seen that peek response for $K_{p\omega}$ higher than 10 is acceptable.

Then, $K_{i\omega}$ is to be defined. Firstly, time constant of the inner control loop is defined as:

$$T_{i,cc} = \frac{L_{cc}}{R_s} \tag{77}$$

According to the symmetrical optimum method [13] integration time constant of the outer loop circuit should be:

$$T_{i\omega} = 4T_{i,cc} \tag{78}$$

Finally, $K_{i\omega}$ can be defined as:

$$K_{i\omega} = \frac{K_{p\omega}}{T_{i\omega}} \tag{79}$$

Transfer function of the open loop flux control could be obtained:

$$G_{\psi,ol}(s) = \frac{K_{p\psi}\left(T_{i\psi}s + 1\right)}{T_{i\psi}s}\frac{a_{cc}}{s + a_{cc}}\frac{1}{s} \tag{80}$$

It could be seen that the only difference between speed Eq. (75) and flux Eq. (80) transfer functions is in the inertia factor J. That is why the flux control stability is analyzed in a similar way as it is done for the speed control loop.

4.2 Simulation

To make a comparison between nonlinear and linear control systems, simulation studies have been done. Starting process of lower power (8.1 kVA) SM1 and higher power (1.56 MVA) SM2 synchronous machines have been simulated. Simulations have been obtained in the same file under the same circumstances. Machines were controlled only through the inverter that was connected to the stator winding. On the rotor winding constant nominal voltage was applied. Nonlinear control system have used reduced order observer, while linear control system have used damper winding currents directly from the SM model. Therefore, some advantage was given to the linear control system. Parameters of the synchronous machines have been given in Appendix.

4.2.1 Results for SM1

In **Figure 5**, results for the starting of the SM1 have been given. It includes rotor speed, electromagnetic torque, rotor speed error and stator flux error. It could be seen that rotor speed error is significantly higher for the linear control system.

4.2.2 Results for SM2

In **Figure 6**, results for the starting of the SM2 have been given. Rotor speed error for the linear control system is again significantly higher. Electromagnetic

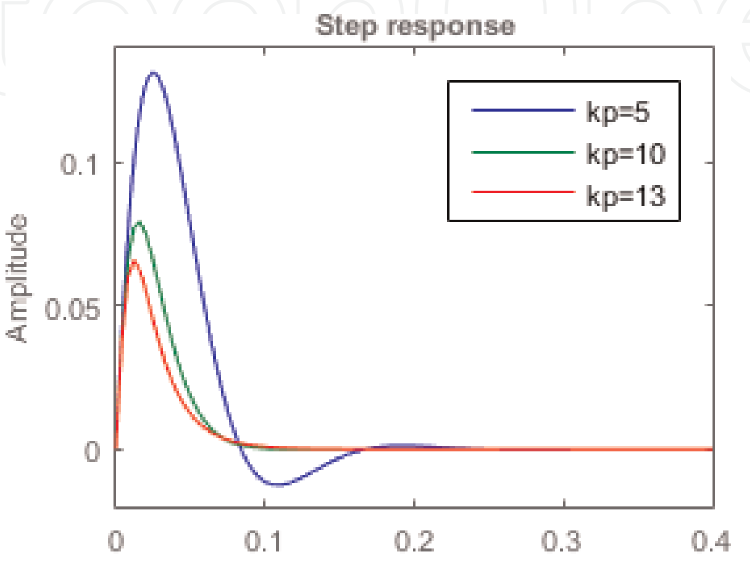

Figure 4.
Step response for input disturbance.

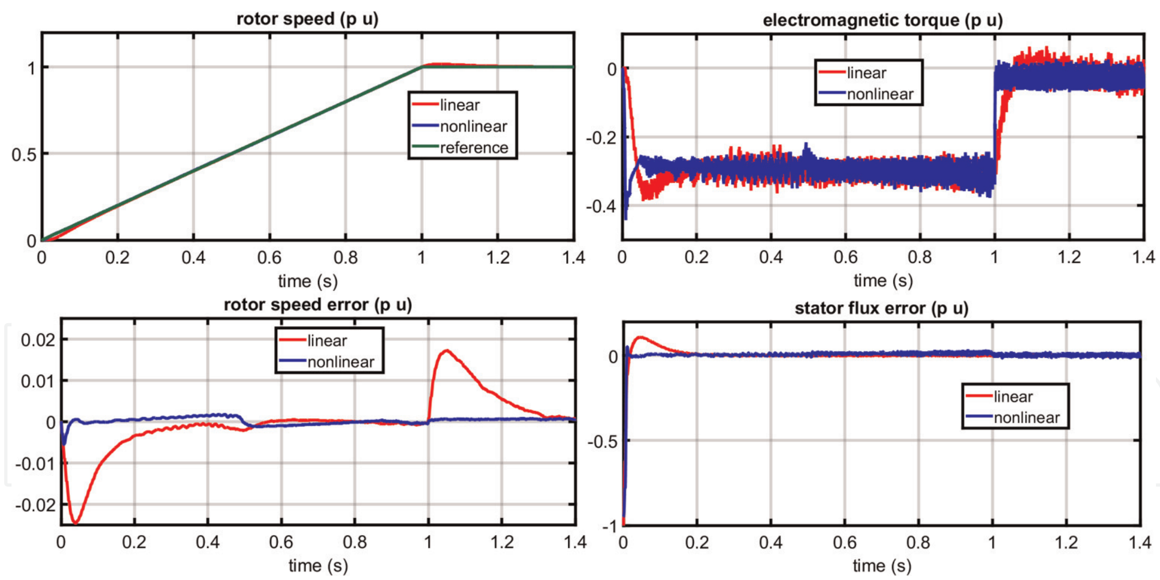

Figure 5.
SM1 comparison.

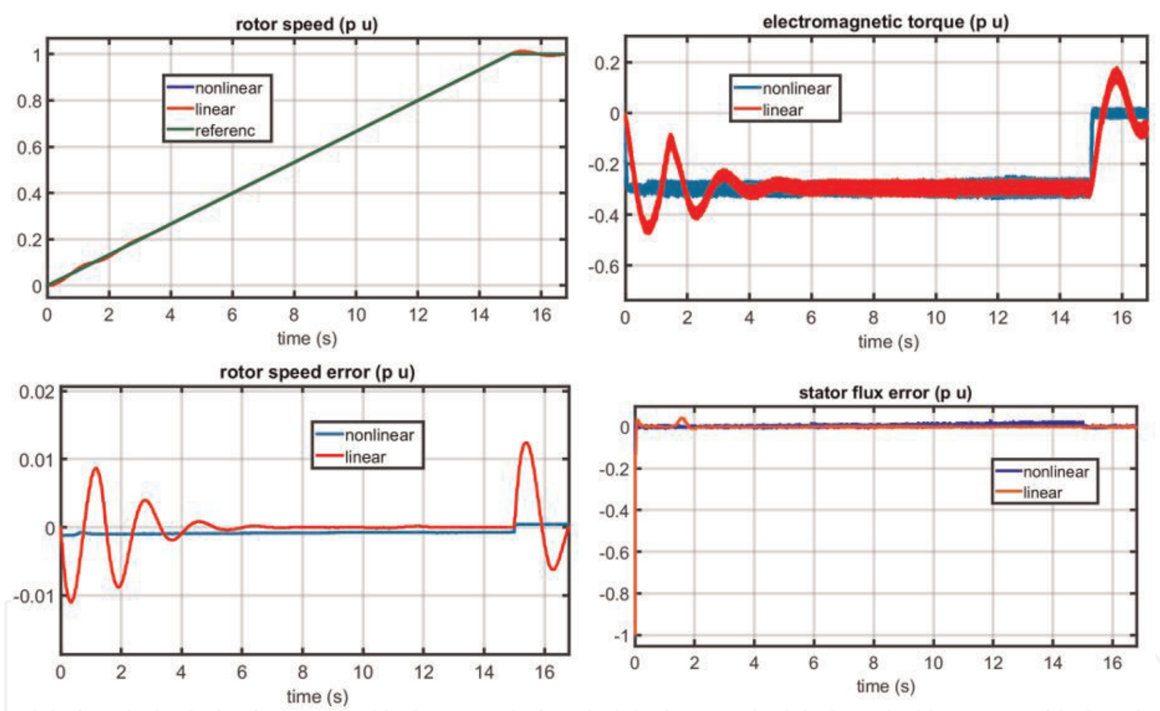

Figure 6.
SM2 comparison.

torque in linear control has some oscillations at the beginning and at reaching of the nominal speed.

5. Processor in the loop testing

Model based development is an approach that can handle complexities of various range of products. It is primarily used for early error detection. Using that approach, control system can be tested in phases. The first phase is called model in the loop (MiL) testing, the second one is processor in the loop (PiL) and finally there is hardware in the loop (HiL). In this work except from MiL, also PiL testing has been done. The testing equipment consists of:

- Matlab Simulink R2015a, OS Windows 7
- Code Composer Studio CCSv5
- TI C2000, C2834x control card
- TMS320C2000 XDSv1 docking station

Data exchange between Simulink model and C2834x control card has been done in real time by serial RS232 communication. During the PiL testing, data precision has to be reduced from double to single. For this reason some error in performance is expected.

5.1 Testing scheme

In **Figure 7**, the scheme of PiL testing system is given. In the Simulink model energetic part (SM, inverter and DC source) has been running, while the complete control system has been running on the processor.

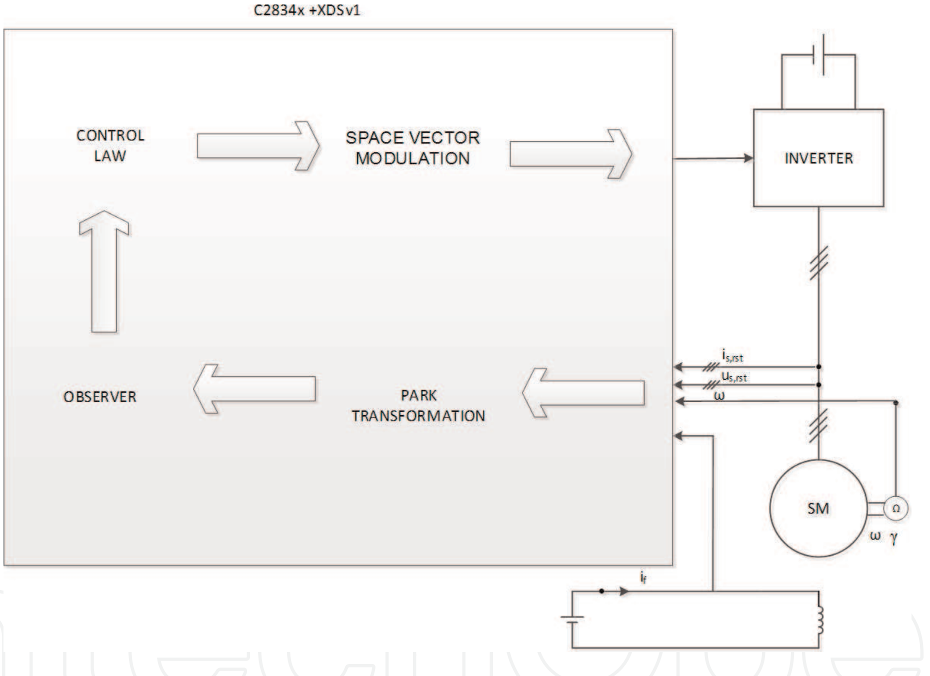

Figure 7.
PiL testing scheme.

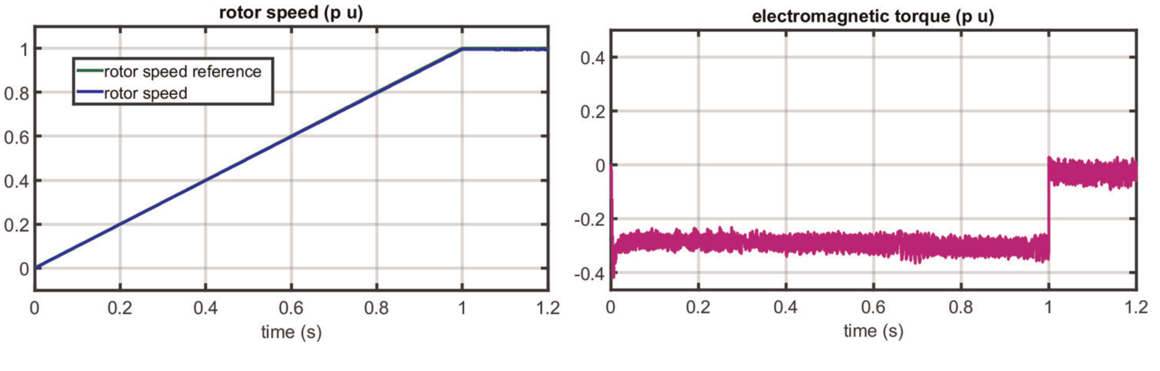

Figure 8.
Starting of SM1-PiL.

To check the novel control algorithm PiL, testing of both (SM1 and SM2) machines have been done. Testing included starting process, reversing of the speed and load step changes.

5.2 PiL testing of SM1

In **Figure 8**, results for the starting of the SM1 have been given. Tracking of the reference speed is precise.

In **Figure 9**, results for the reversing of the speed of the SM1 have been given. Tracking of the reference speed is again obtained precisely.

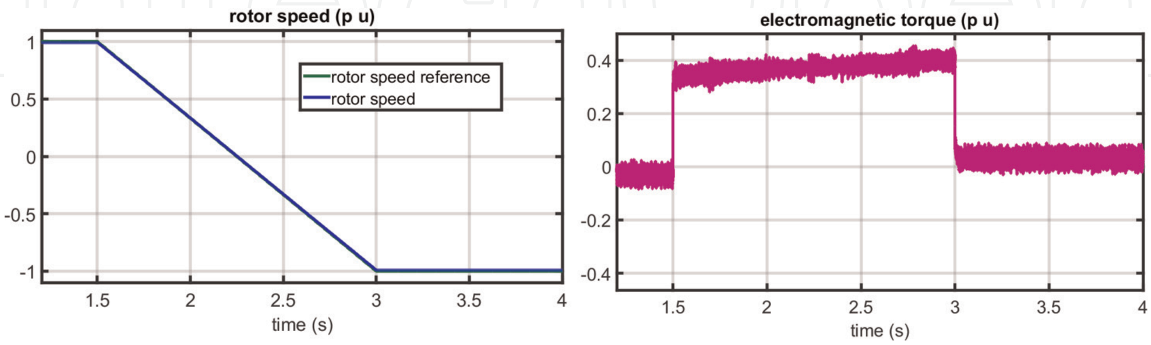

Figure 9.
Reversing of the speed of SM1-PiL.

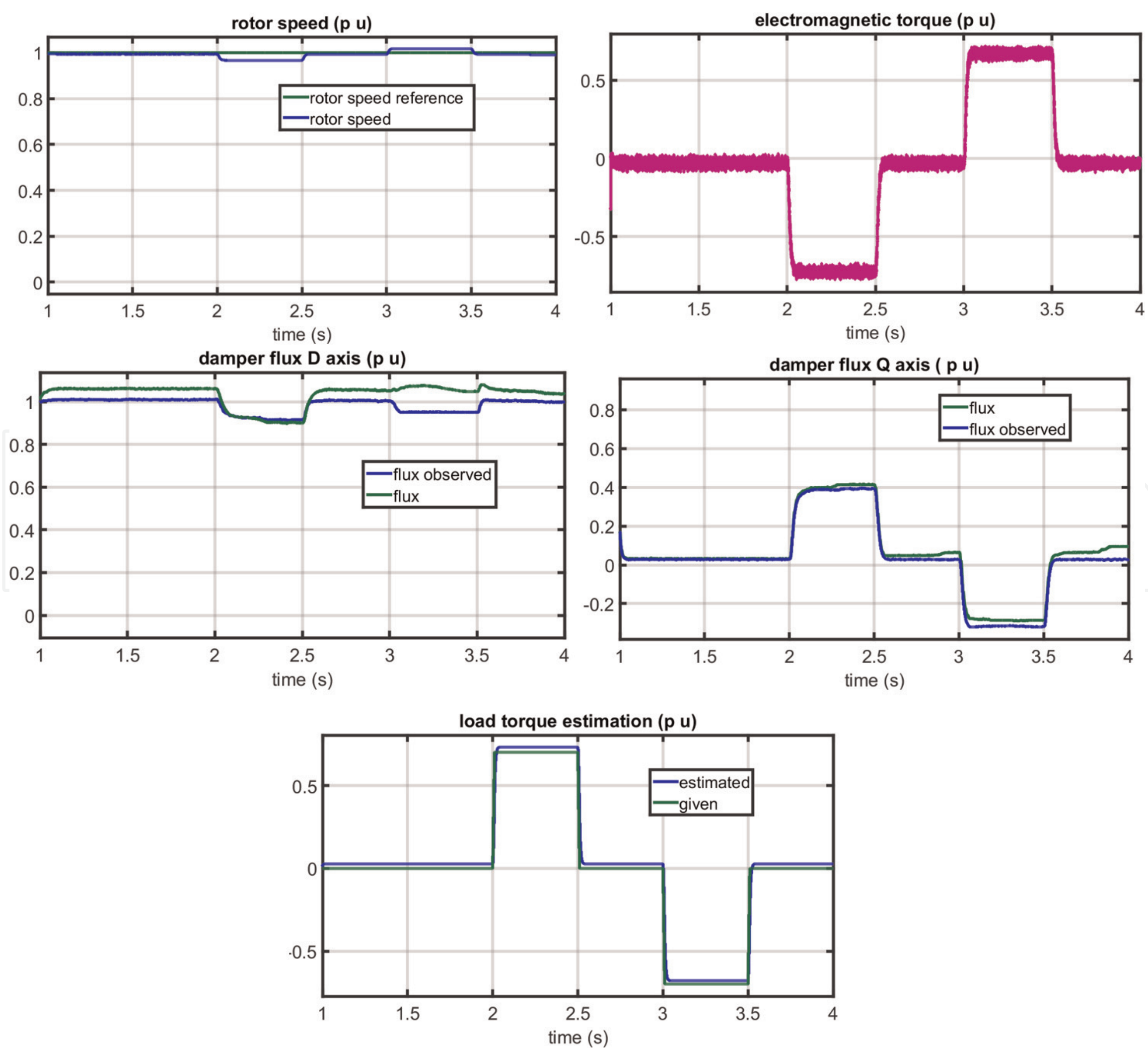

Figure 10.
Load step changes of SM1-PiL.

DOI: http://dx.doi.org/10.5772/intechopen.89420

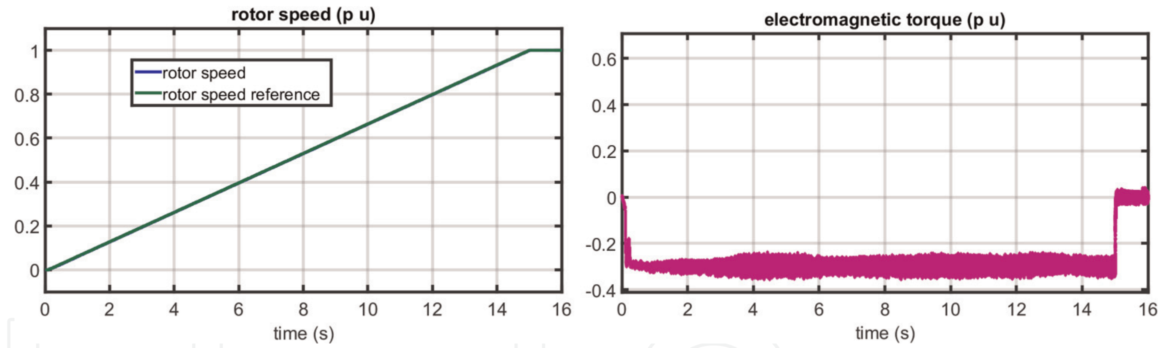

Figure 11.
Starting of SM2-PiL.

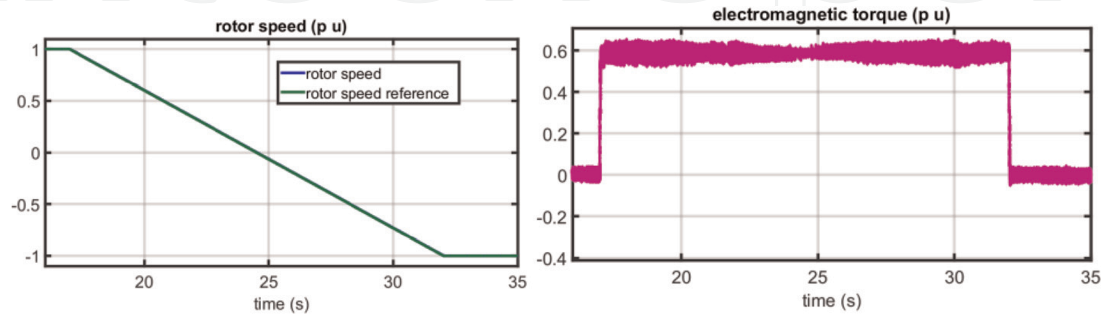

Figure 12.
Reversing of the speed of SM2-PiL.

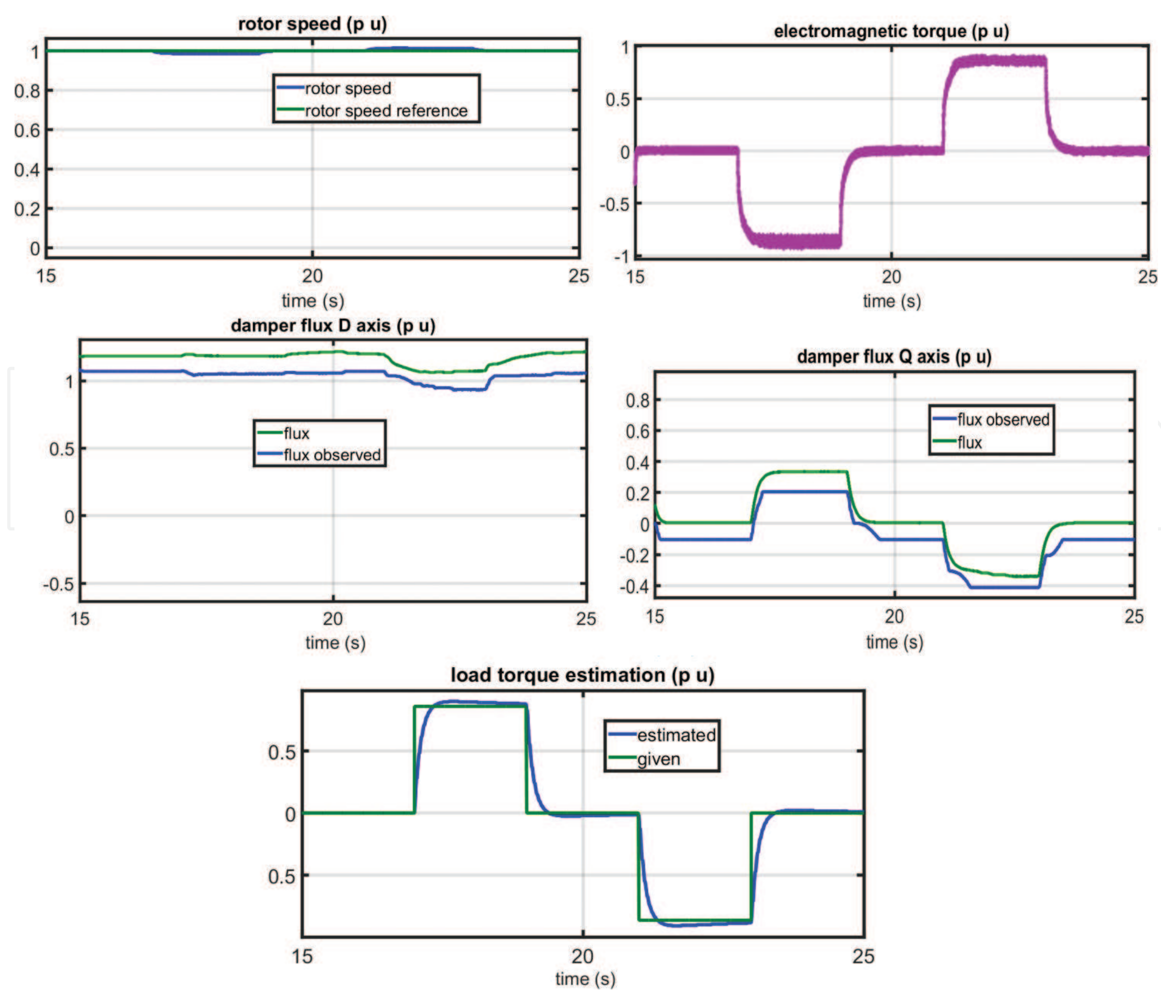

Figure 13.
Load step changes of SM2-PiL.

In **Figure 10**, results for the load step changes of the SM1 have been given. The step change is from no load to 100% of the nominal load. Except from rotor speed and electromagnetic torque, results of damper flux observer and load torque estimation are also given.

There is an error of about 10% in observer operation, and an error in load torque estimator of about 5%. This is due to reduction in data precision during PiL testing. In spite of that, an error in speed tracking exists only during the step change and it is about 3%.

5.3 PiL testing of SM2

In **Figure 11**, results for the starting of the SM2 have been given. Tracking of the reference speed is precise.

In **Figure 12**, results for the reversing of the speed of the SM2 have been given. Tracking of the reference speed is again obtained precisely.

In **Figure 13**, results for the load step changes of the SM2 have been given. The step change is from no load to 100% of the nominal load. Except from rotor speed and electromagnetic torque, results of damper flux observer and load torque estimation has been also given.

There is an error of about 15% in observer operation, and an error in load torque estimator of about 3%. This is due to reduction in data precision during PiL testing. In spite of that, an error in speed tracking exist only during the step change and it is about 2%.

6. Conclusion

Dynamical system of SM is characterized with high nonlinearity, variable coupling and unknown damper winding variables. If the control of the SM is done by the classical linear control system, its complexity has to be simplified. Usually, dynamics of the damper winding are neglected. Besides, classical control use currents components controllers to obtain torque and flux control. Coupling in the SM dynamical system makes that change of any current component necessary changes both; torque and flux. Due to these reasons, classical system cannot provide efficient control system with good dynamic performance.

Using nonlinear techniques, fully decoupled torque and flux control could be obtained. To make it applicable, damper windings states should be known. In this work, using damper winding observers and nonlinear control law, a high performance rotor speed tracking system is obtained. Full order and reduced order deterministic observers of damper winding currents and damper winding fluxes are presented. Nonlinear control law is obtained using feedback linearization method.

A comparison between classical linear system and novel control system has been done. At the beginning of the starting as well as at reaching of the nominal speed classical control system exhibits oscillations, while the novel control keeps tracking precisely.

Processor in the loop testing of the novel control system has been also done. Except from damper winding flux observer, load torque estimation has been also used. The system performance during starting, reversing of the speed and during load step changes has been tested. Due to reduction in data precision, some error of the damper flux observer and load torque estimator appears. In spite of that, performance of the rotor speed tracking system is precise.

It could be concluded that proposed control system has advantages over classical and gives some new opportunities.

Appendix

Synchronous machine SM 1 parameters:

Power S_n: 8.1 (kVA), Voltage U_n: 400 (V), pole pairs p: 2, frequency f_{n}: 50 (Hz), stator winding resistance R_{s}: 0.082 (p.u.), stator winding leakage inductance $L_{\sigma\mathrm{s}}$: 0.072 (p.u.), mutual inductance d-axes L_{md}: 1.728 (p.u.), mutual inductance q-axes L_{mq}: 0.823 (p.u.), rotor winding resistance R_{f}: 0.0612 (p.u.), rotor winding leakage inductance $L_{\sigma\mathrm{f}}$: 0.18 (p.u.), damper winding resistance d-axes R_{D}: 0.159 (p.u.), damper winding leakage inductance d-axes $L_{\sigma\mathrm{D}}$: 0.117 (p.u.), damper winding resistance q-axes R_{Q}: 0.242 (p.u.), damper winding leakage inductance q-axes $L_{\sigma\mathrm{Q}}$: 0.162 (p.u.), Inertia constant H: 0.14 (s).

Synchronous machine SM 2 parameters:

Power S_n: 1560 (kVA), Voltage U_n: 6300 (V), pole pairs p: 5, frequency f_{n}: 50 (Hz), stator winding resistance R_{s}: 0.011 (p.u.), stator winding leakage inductance $L_{\sigma\mathrm{s}}$: 0.148 (p.u.), mutual inductance d-axes L_{md}: 1.177 (p.u.), mutual inductance q-axes L_{mq}: 0.622 (p.u.), rotor winding resistance R_{f}: 0.0017 (p.u.), rotor winding leakage inductance $L_{\sigma\mathrm{f}}$ (p.u.): 0,186, damper winding resistance d-axes R_{D}: 0.0481 (p.u.), damper winding leakage inductance d-axes $L_{\sigma\mathrm{D}}$: 0.096 (p.u.), damper winding resistance q-axes R_{Q}: 0.0256 (p.u.), damper winding leakage inductance q-axes $L_{\sigma\mathrm{Q}}$: 0.0509 (p.u.), Inertia constant H: 2.2 (s).

Author details

Marijo Šundrica
Končar—Power Plant and Electric Traction Engineering, Zagreb, Croatia

*Address all correspondence to: marijo.sundrica@koncar-ket.hr

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