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Nonlinear Observer-based Control of Synchronous Machine Drive System

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Abstract – Starting from a new dynamic system description novel synchronous machine deterministic observers are proposed. Reduced and full order adaptive observer variations are presented. Based on the feedback linearization control law and the use of deterministic observer a novel control system is built. It meets the requirements of high performance tracking system. Adaptivity to stator and rotor resistance and the torque sensorless application is included. The comparison of the proposed novel control with conventional linear and nonlinear control systems is discussed. The given simulational study includes complete drive system integration.

Keywords: Adaptive control, Linearization techniques, Motor drives, Nonlinear control systems, Observers

1. Introduction

This work examines a novel control method for variable speed operation of a synchronous machine. Here, it is assumed that the synchronous machine (SM) has damper windings and a separate excitation winding.

Variable speed operation of SM is used in various cases of power generation and electric drive applications. In windmill power generation and in hydro power units, variable speed operation is a design requirement. SM drive finds particular applications in: coal mines, the metal and cement industries, ship propulsion etc. 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 a high performance tracking system it is necessary to have an adequate observer for these states, as is done in similar AC drive systems [1]. There are not many studies, either linear (vector) or nonlinear, of the SM control system.

AC motor vector control is 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 true, but if this method is used for SM control the q-current component will essentially change the flux [2]. In this case it is said that the control is coupled and this is why SM vector control is not efficient enough. There are few ideas on how to solve this problem. One involves coordinate transformation [3, 4]. Unfortunately, a control system with many calculations (coordinate transformations, PI controllers, and other) has to be used. Because of its complexity, further development of this control does not look promising. In standard SM control systems the damper winding effect is neglected. It is well known that damper windings have positive influence on SM stability at power system nominal operation. Its importance in asynchronous starting process is also known. During synchronous starting its effect has not been studied yet, but it would be of interest especially in the case of high performance drives.

Regarding nonlinear control SM applications, a few methods are used: backstepping [5], passivity [6] and adaptive Lyapunov based [7, 8]. The passive method [6] fails to give better results and the backstepping [5] method fails to take the damper windings into consideration. In [7, 8] new algorithms are proposed, but their complexity seems to make implementation impractical.

In general practice, the stability in many nonlinearly controlled AC drives is proved by Lyapunov [9]. This is done for the observer as for the whole system (observer + controller) [10-13] if necessary. Except for the missing states, the control also includes parameter variation. To achieve this, many different control methods are combined with various observers. For example, forced dynamic control is combined with sliding mode observer or model reference system [14-17]. Stability can be achieved for winding resistance change [18] or change of inductance and motor inertia [19]. Also, sensorless control can be achieved in regard to load torque [20-22] or rotor speed [23, 24]. The aim of this work is to use nonlinear techniques to develop a novel control system for SM. By using completely decoupled control law and by taking into consideration the effect of damper windings, the resulting control system is made more advantageous than the existing SM control systems.

This paper is organized so as to give the complete control system modeling: the SM system and its observ-

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ability analysis, observer and control law definitions and internal dynamics analysis. An extensive simulation study is then presented. The results of various observer applications and also the comparisons with linear and nonlinear control systems are given.

2. Modeling

2.1 SM system

In order to take into consideration the effect of the damper winding, the system given in (1) will be the starting point of analysis.

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_f \\ \dot{\varphi}_D \\ \dot{i}_q \\ \dot{\varphi}_Q \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} a_1 i_d + a_2 i_f + a_3 i_q \omega + a_4 \varphi_D + a_5 \varphi_Q \omega + a_6 u_d + a_7 u_f \\ b_1 i_d + b_2 i_f + b_3 i_q \omega + b_4 \varphi_D + b_5 \varphi_Q \omega + b_6 u_d + b_7 u_f \\ c_1 i_d + c_2 i_f + c_3 \varphi_D \\ d_1 i_q + d_2 i_d \omega + d_3 i_f \omega + d_4 \omega \varphi_D + d_5 \varphi_Q + d_6 u_q \\ f_1 i_q + f_2 \varphi_Q \\ g_1 i_d i_q + g_2 i_f i_q + g_3 i_q \varphi_D + g_4 i_d \varphi_Q + g_5 T_L \end{bmatrix} \quad (1)$$

Coefficients a_1, a_2 etc. are calculated from SM parameters:

$a_1=(L_f L_{md}^2 r_D - L_{md}^3 r_D + L_D^2 L_f r_s - L_D L_{md}^2 r_s) / (L_D A)$
$a_2=(L_f L_{md}^2 r_D - L_{md}^3 r_D - L_D^2 L_{md} r_f + L_D L_{md}^2 r_f) / (L_D A)$
$a_3=(L_D^2 L_f L_{mq}^2 - L_D L_{md}^2 L_{mq}^2 - L_D^2 L_f L_q L_Q + L_D L_{md}^2 L_q L_Q) / (L_D L_Q A)$
$a_4=(-L_f L_{md} L_Q r_D + L_{md}^2 L_Q r_D) / (L_D L_Q A)$
$a_5=(-L_D^2 L_f L_{mq} + L_D L_{md}^2 L_{mq}) / (L_D L_Q A)$
$a_6=(-L_D^2 L_f L_Q + L_D L_{md}^2 L_Q) / (L_D L_Q A)$
$a_7=(L_D^2 L_{md} L_Q - L_D L_{md}^2 L_Q) / (L_D L_Q A)$
$b_1=(L_d L_{md}^2 r_D - L_{md}^3 r_D - L_D^2 L_{md} r_s + L_D L_{md}^2 r_s) / (L_D A)$
$b_2=(L_d L_{md}^2 r_D - L_{md}^3 r_D + L_d L_D^2 r_f - L_D L_{md}^2 r_f) / (L_D A)$
$b_3=(-L_D^2 L_{md} L_{mq}^2 + L_D L_{md}^2 L_{mq}^2 + L_D^2 L_{md} L_q L_Q - L_D L_{md}^2 L_q L_Q)/(L_D L_Q A)$
$b_4=(-L_d L_{md} L_Q r_D + L_{md}^2 L_Q r_D)/ (L_D L_Q A)$
$b_5=(L_D^2 L_{md} L_{mq} - L_D L_{md}^2 L_{mq})/ (L_D L_Q A)$
$b_6=(L_D^2 L_{md} L_Q - L_D L_{md}^2 L_Q)/ (L_D L_Q A)$
$b_7=(-L_d L_D^2 L_Q + L_D L_{md}^2 L_Q)/ (L_D L_Q A)$
$c_1=L_{md} r_D/L_D$
$c_2=L_{md} r_D/L_D$
$c_3= -r_D/L_D$
$d_1=(-L_D L_{mq}^2 r_Q - L_D L_Q^2)/ (L_D L_Q B)$
$d_2=(-L_d L_D L_Q^2 + L_{md}^2 L_Q^2) / (L_D L_Q B)$
$d_3=(-L_D L_{md} L_Q^2 + L_{md}^2 L_Q^2) / (L_D L_Q B)$
$d_4=- (L_{md} L_Q) / (L_D B)$
$d_5=(L_{mq} r_Q) / (L_Q B)$
$d_6=L_Q$
$f_1=(L_{mq} r_Q)/L_Q$
$f_2= -r_Q/L_Q$
$g_1= - (L_D L_{md} L_{mq} - L_D L_{md} L_Q + L_{md}^2 L_Q + L_D L_{mq} L_Q) / (2 H L_D L_Q)$
$g_2= - (-L_D L_{md} L_Q + L_{md}^2 L_Q)/(2 H L_D L_Q)$
$g_3= L_{md}/(2 H L_D)$
$g_4= L_{md}/(2 H L_Q)$
$g_5= -1/(2 H)$
$A = -L_d L_D L_f + L_d L_{md}^2 + L_D L_{md}^2 + L_f L_{md}^2 - 2 L_{md}^3$
$B= -L_{mq}^2 + L_q L_Q$

2.2 Observability analysis

Observability of the given system (1) is analysed. Here, measured states are given as:

$$h_1=i_d,\ h_2=i_f,\ h_3=i_q,\ h_4=\omega.$$

The analysis is based on nonlinear system local weak observability concept [25, 26].

Assume a nonlinear dynamical system Σ (2):

$$\Sigma: \begin{aligned} \frac{dx}{dt} &= f(x,u) \\ y &= h(x) \end{aligned} \quad (2)$$

In a point from its state space $x_0 \in \Omega$ its observability matrix is (3):

$$O = \frac{\partial L}{\partial x}\Big|_{x=x0} \quad (3)$$

where
$$L = \begin{bmatrix} L_f^0 h \\ L_f h \\ . \\ . \\ . \\ L_f^{n-1} h \end{bmatrix} \quad (4)$$

is observability criterion matrix and L^k_f is the k-th order Lie derivative of the function h with respect to the vector field f. If the matrix O has full rank

$$\text{rank}\ \{O\}=n$$

than the state of the system Σ is locally weakly observable at point x_0.

A number of possible submatrices can be tested, but choosing matrices given in (5) and (6) it will be easy to make a proof.

$$O_1=\begin{bmatrix} dh_1\\ dh_2\\ dh_3\\ dh_4\\ d(L_f h_1)\\ d(L_f h_2)\end{bmatrix}=\begin{bmatrix} \frac{\partial L_f^0 h_1}{\partial i_d} & \frac{\partial L_f^0 h_1}{\partial i_f} & \frac{\partial L_f^0 h_1}{\partial \phi_D} & \frac{\partial L_f^0 h_1}{\partial i_q} & \frac{\partial L_f^0 h_1}{\partial \phi_Q} & \frac{\partial L_f^0 h_1}{\partial \omega}\\ \frac{\partial L_f^0 h_2}{\partial i_d} & \frac{\partial L_f^0 h_2}{\partial i_f} & \frac{\partial L_f^0 h_2}{\partial \phi_D} & \frac{\partial L_f^0 h_2}{\partial i_q} & \frac{\partial L_f^0 h_2}{\partial \phi_Q} & \frac{\partial L_f^0 h_2}{\partial \omega}\\ \frac{\partial L_f^0 h_3}{\partial i_d} & \frac{\partial L_f^0 h_3}{\partial i_f} & \frac{\partial L_f^0 h_3}{\partial \phi_D} & \frac{\partial L_f^0 h_3}{\partial i_q} & \frac{\partial L_f^0 h_3}{\partial \phi_Q} & \frac{\partial L_f^0 h_3}{\partial \omega}\\ \frac{\partial L_f^0 h_4}{\partial i_d} & \frac{\partial L_f^0 h_4}{\partial i_f} & \frac{\partial L_f^0 h_4}{\partial \phi_D} & \frac{\partial L_f^0 h_4}{\partial i_q} & \frac{\partial L_f^0 h_4}{\partial \phi_Q} & \frac{\partial L_f^0 h_4}{\partial \omega}\\ \frac{\partial L_f^1 h_1}{\partial i_d} & \frac{\partial L_f^1 h_1}{\partial i_f} & \frac{\partial L_f^1 h_1}{\partial \phi_D} & \frac{\partial L_f^1 h_1}{\partial i_q} & \frac{\partial L_f^1 h_1}{\partial \phi_Q} & \frac{\partial L_f^1 h_1}{\partial \omega}\\ \frac{\partial L_f^1 h_2}{\partial i_d} & \frac{\partial L_f^1 h_2}{\partial i_f} & \frac{\partial L_f^1 h_2}{\partial \phi_D} & \frac{\partial L_f^1 h_2}{\partial i_q} & \frac{\partial L_f^1 h_2}{\partial \phi_Q} & \frac{\partial L_f^1 h_2}{\partial \omega}\end{bmatrix} \quad (5)$$

$$O_2=\begin{bmatrix} dh_1\\ dh_2\\ dh_3\\ dh_4\\ d(L_f h_1)\\ d(L_f h_3)\end{bmatrix}=\begin{bmatrix} \frac{\partial L_f^0 h_1}{\partial i_d} & \frac{\partial L_f^0 h_1}{\partial i_f} & \frac{\partial L_f^0 h_1}{\partial \phi_D} & \frac{\partial L_f^0 h_1}{\partial i_q} & \frac{\partial L_f^0 h_1}{\partial \phi_Q} & \frac{\partial L_f^0 h_1}{\partial \omega}\\ \frac{\partial L_f^0 h_2}{\partial i_d} & \frac{\partial L_f^0 h_2}{\partial i_f} & \frac{\partial L_f^0 h_2}{\partial \phi_D} & \frac{\partial L_f^0 h_2}{\partial i_q} & \frac{\partial L_f^0 h_2}{\partial \phi_Q} & \frac{\partial L_f^0 h_2}{\partial \omega}\\ \frac{\partial L_f^0 h_3}{\partial i_d} & \frac{\partial L_f^0 h_3}{\partial i_f} & \frac{\partial L_f^0 h_3}{\partial \phi_D} & \frac{\partial L_f^0 h_3}{\partial i_q} & \frac{\partial L_f^0 h_3}{\partial \phi_Q} & \frac{\partial L_f^0 h_3}{\partial \omega}\\ \frac{\partial L_f^0 h_4}{\partial i_d} & \frac{\partial L_f^0 h_4}{\partial i_f} & \frac{\partial L_f^0 h_4}{\partial \phi_D} & \frac{\partial L_f^0 h_4}{\partial i_q} & \frac{\partial L_f^0 h_4}{\partial \phi_Q} & \frac{\partial L_f^0 h_4}{\partial \omega}\\ \frac{\partial L_f^1 h_1}{\partial i_d} & \frac{\partial L_f^1 h_1}{\partial i_f} & \frac{\partial L_f^1 h_1}{\partial \phi_D} & \frac{\partial L_f^1 h_1}{\partial i_q} & \frac{\partial L_f^1 h_1}{\partial \phi_Q} & \frac{\partial L_f^1 h_1}{\partial \omega}\\ \frac{\partial L_f^1 h_3}{\partial i_d} & \frac{\partial L_f^1 h_3}{\partial i_f} & \frac{\partial L_f^1 h_3}{\partial \phi_D} & \frac{\partial L_f^1 h_3}{\partial i_q} & \frac{\partial L_f^1 h_3}{\partial \phi_Q} & \frac{\partial L_f^1 h_3}{\partial \omega}\end{bmatrix} \quad (6)$$

O_1 determinant is:

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

Det $O_1 \neq 0$, for $\omega \neq 0$

O_2 determinant is:

$$Det(O_2)=-\frac{L_{md}\omega^2\left(-L_D^2 L_f L_{mq}+L_D L_{md}^2 L_{mq}\right)}{ABL_D^2}-\frac{L_{mq} r_Q\left(-L_f L_{md} L_Q r_D+L_{md}^2 L_Q r_D\right)}{ABL_Q^2 L_D}$$

Det $O_2 \neq 0$, for $\omega = 0$

Considering both conditions:

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

Matrix O is a full-rank matrix and it can be concluded that the system is weakly locally observable at every point of state space Ω.

2.3 Deterministic observers

After the successful observability analysis, an observer can be constructed. Damper winding fluxes are missing states. In addition to observing the missing states, it would be preferable for the observer to be adaptive to parameter changes.

A new observer adaptive to stator and rotor winding resistance is presented.

The idea is to extend (1) in a way that stator and rotor resistances can be separately collected. The resulting system is given in (7).

$$\begin{bmatrix}\dot{i}_d\\ \dot{i}_f\\ \dot{\phi}_D\\ \dot{i}_q\\ \dot{\phi}_Q\\ \dot{\omega}\end{bmatrix}=\begin{bmatrix} a_1 i_d+a_2 i_f+a_3 i_q\omega+a_4\phi_D+a_5\phi_Q\omega+a_6 i_f R_f+a_7 i_d R_s+a_8 u_d+a_9 u_f\\ b_1 i_d+b_2 i_f+b_3 i_q\omega+b_4\phi_D+b_5\phi_Q\omega+b_6 i_f R_f+b_7 i_d R_s+b_8 u_d+b_9 u_f\\ c_1 i_d+c_2 i_f+c_3\phi_D\\ d_1 i_q+d_2 i_d\omega+d_3 i_f\omega+d_4\omega\phi_D+d_5\phi_Q+d_6 i_q R_s+d_7 u_q\\ f_1 i_q+f_2\phi_Q\\ g_1 i_d i_q+g_2 i_f i_q+g_3 i_q\phi_D+g_4 i_d\phi_Q+g_5 T_L\end{bmatrix} \quad (7)$$

Coefficients a_1, a_2 etc. are very similar to the already

$$\begin{bmatrix}\dot{\hat{i}}_d\\ \dot{\hat{i}}_f\\ \dot{\hat{\phi}}_D\\ \dot{\hat{i}}_q\\ \dot{\hat{\phi}}_Q\\ \dot{\hat{\omega}}\end{bmatrix}=\begin{bmatrix} a_1 i_d+a_2 i_f+a_3 i_q\omega+a_4\hat{\phi}_D+a_5\omega\hat{\phi}_Q+a_6 i_f\hat{R}_f+a_7 i_d\hat{R}_s+a_8 u_d+a_9 u_f+k_{11}e_1\\ b_1 i_d+b_2 i_f+b_3 i_q\omega+b_4\hat{\phi}_D+b_5\omega\hat{\phi}_Q+b_6 i_f\hat{R}_f+b_7 i_d\hat{R}_s+b_8 u_d+b_9 u_f+k_{22}e_2\\ c_1 i_d+c_2 i_f+c_3\hat{\phi}_D+k_{31}e_1+k_{32}e_2+k_{33}e_4+k_{34}e_6\\ d_1 i_q+d_2 i_d\omega+d_3 i_f\omega+d_4\omega\hat{\phi}_D+d_5\hat{\phi}_Q+d_6 i_q\hat{R}_s+d_7 u_q+k_{43}e_4\\ f_1 i_q+f_2\hat{\phi}_Q+k_{51}e_1+k_{52}e_2+k_{53}e_4+k_{54}e_6\\ g_1 i_d i_q+g_2 i_f i_q+g_3 i_q\hat{\phi}_D+g_4 i_d\hat{\phi}_Q+g_5 T_L+k_{64}e_6\end{bmatrix} \quad (9)$$

given coefficients.

Consider this observer (8):

$$\begin{bmatrix} \dot{\hat{\phi}}_D \\ \dot{\hat{\phi}}_Q \end{bmatrix} = \begin{bmatrix} c_1 i_d + c_2 i_f + c_3 \hat{\phi}_D \\ f_1 i_q + f_2 \hat{\phi}_D \end{bmatrix} \tag{8}$$

It is Lyapunov stable because c_3 and f_2 are always negative for SM.

Although the observer is simple and stable, it is of a reduced order and because of this it is not possible to prove global stability of the whole system.

Proposition: For the SM model given in (7), a full order stable observer adaptive to stator and rotor resistance change is given in (9).

Proof: Consider Lyapunov function given in (10). It is positive-definite.

$$V_1 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{1}{2}e_3^2 + \frac{1}{2}e_4^2 + \frac{1}{2}e_5^2 + \frac{1}{2}e_6^2 + \frac{1}{2}\Delta R_f^2 + \frac{1}{2}\Delta R_s^2 \tag{10}$$

Error dynamics is defined as (7) - (9) and is given in (11).

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \\ \dot{e}_4 \\ \dot{e}_5 \\ \dot{e}_6 \end{bmatrix} = \begin{bmatrix} a_4 e_3 + a_5 \omega e_5 + a_6 i_f \Delta R_f + a_7 i_d \Delta R_s - k_{11} e_1 \\ b_4 e_3 + b_5 \omega e_5 + b_6 i_f \Delta R_f + b_7 i_d \Delta R_s - k_{22} e_2 \\ c_3 e_3 - k_{31} e_1 - k_{32} e_2 - k_{33} e_4 - k_{34} e_6 \\ d_{d4} \omega e_3 + d_5 e_5 + d_6 i_q \Delta R_s - k_{43} e_4 \\ f_2 e_5 - k_{51} e_1 - k_{52} e_2 - k_{53} e_4 - k_{54} e_6 \\ g_3 i_q e_3 + g_4 i_d e_5 - k_{64} e_6 \end{bmatrix} \tag{11}$$

State errors are:

$$e_1 = i_d - \hat{i}_d;\ e_2 = i_f - \hat{i}_f;\ e_3 = \phi_D - \hat{\phi}_D;\ e_4 = i_q - \hat{i}_q;$$
$$e_5 = \phi_Q - \hat{\phi}_Q;\ e_6 = \omega - \hat{\omega}$$

and resistance errors: ΔR_s and ΔR_f.

Now consider Lyapunov function differential taking into account its error dynamics (11) and the usual assumption of slow resistance change:

$$\begin{aligned} \dot{V}_1 = {} & a_4 e_1 e_3 + a_5 \omega e_1 e_5 + a_6 i_f e_1 \Delta R_f + a_7 i_d e_1 \Delta R_s - k_{11} e_1^2 + \\ & + b_4 e_2 e_3 + b_5 \omega e_2 e_5 + b_6 i_f e_2 \Delta R_f + b_7 i_d e_1 \Delta R_s - k_{22} e_2^2 + \\ & + c_3 e_3^2 - k_{31} e_1 e_3 - k_{32} e_2 e_3 - k_{33} e_3 e_4 - k_{34} e_3 e_6 + \\ & + d_4 \omega e_3 e_4 + d_5 e_4 e_5 + d_6 i_q e_4 \Delta R_s - k_{43} e_4^2 + \\ & + f_2 e_5^2 - k_{51} e_1 e_5 - k_{52} e_2 e_5 - k_{53} e_4 e_5 - k_{54} e_5 e_6 + \\ & + g_3 i_q e_3 e_4 + g_4 i_d e_5 e_6 - k_{64} e_6^2 - \Delta R_s \dot{\hat{R}}_s - \Delta R_f \dot{\hat{R}}_f \end{aligned}$$

with convergence coefficients k_{11}, k_{22}, etc. given as:

$$k_{31} = a_4;\ k_{32} = b_4;\ k_{33} = d_4\omega;\ k_{34} = g_3 i_q;\ k_{51} = a_5\omega;\ k_{52} = b_5\omega;$$
$$k_{53} = d_5\ k_{54} = g_4 i_d;\ k_{11},\ k_{22},\ k_{43},\ k_{64} > 0$$

and resistance adaptive rules (12), (13):

$$\dot{\hat{R}}_f = a_6 i_f e_1 + b_6 i_f e_2 \tag{12}$$

$$\dot{\hat{R}}_s = a_7 i_d e_1 + b_7 i_d e_2 + d_6 i_q e_4 \tag{13}$$

Lyapunov function differential is obtained (14):

$$\dot{V}_1 = -k_{11} e_1^2 - k_{22} e_2^2 + c_3 e_3^2 - k_{43} e_4^2 + f_2 e_5^2 - k_{64} e_6^2 \tag{14}$$

it is negative-definite and according to Lyapunov direct method global asymptotic stability of the observer is proved.

2.4 Control law

The aim of nonlinear control is to achieve decoupling between flux and torque controls. As already stated, the feedback linearization method is chosen.

The control demand is to make a tracking system of two outputs (15): rotor speed, and square of stator magnetic flux:

$$\hat{h}_1 = \hat{\omega};\quad \hat{h}_2 = \hat{\phi}_d^2 + \hat{\phi}_q^2 \tag{15}$$

φ_d, φ_q are stator magnetic fluxes; not to be misinterpreted as φ_D, φ_Q that are damper winding fluxes used as state variables.

Although it is possible to include excitation control, excitation voltage will remain constant.

It is necessary to separate the first output into two variables; so a new one $\hat{h}_{11}$ (electromagnetic torque) is introduced.

After some algebra, the system will get the form of (16):

$$\begin{bmatrix} \dot{\hat{h}}_{11} \\ \dot{\hat{h}}_2 \end{bmatrix} = \begin{bmatrix} L_{\hat{f}} \hat{h}_{11} \\ L_{\hat{f}} \hat{h}_2 \end{bmatrix} + G \begin{bmatrix} u_d \\ u_q \end{bmatrix} \tag{16}$$

where G is decoupling matrix: $G = \begin{bmatrix} L_{g1}\hat{h}_{11} \cdot L_{g2}\hat{h}_{11} \\ L_{g1}\hat{h}_2\ L_{g2}\hat{h}_2 \end{bmatrix}$.

Now, after the control law (17) is defined:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = G^{-1} \begin{bmatrix} L_{\hat{f}} \hat{h}_{11} - k_{p1} e_8 + \dot{h}_{11ref} + h_{11ref} - e_7 \\ -L_{\hat{f}} \hat{h}_2 - k_{p2} e_9 + \dot{h}_{2ref} \end{bmatrix} \tag{17}$$

with errors: $e_7 = \hat{h}_1 - h_{1ref}$; $e_8 = \hat{h}_{11} - h_{11ref}$; $e_9 = \hat{h}_2 - h_{2ref}$.

Similarly to [27], error dynamics is gained and decoupling is achieved (18):

$$\begin{bmatrix} \dot{e}_7 \\ \dot{e}_8 \\ \dot{e}_9 \end{bmatrix} = \begin{bmatrix} e_8 - k_{p0} e_7 \\ -k_{p1} e_8 - e_7 \\ -k_{p2} e_9 \end{bmatrix} \tag{18}$$

It is easy to make the Lyapunov proof of this error dynamics as well as to prove the convergence of the whole system (observer + controller). Consider positive-definite Lyapunov function V_2 (19):

$$V_2 = \frac{1}{2} e_7^2 + \frac{1}{2} e_8^2 + \frac{1}{2} e_9^2 \tag{19}$$

By using positive coefficients k_{p0}, k_{p1} and k_{p2}, the differential of V_2 is negative-definite and global asymptotic stability of the control law is obtained according to Lyapunov direct method.

Both functions V_1 and V_2 are Lyapunov stable, and it is concluded that dynamics of the entire system (V_1+ V_2) is stable.

2.5 Internal dynamics

It is not possible to obtain exact linearization for the SM system as well as some similar systems such as the induction motor [28]. That is why partial input-output linearization has been applied. The relative degree of the system is lower than the system order, so it is necessary to check the system's internal dynamics.

In the well known theorem of bounded function it is stated that the sum and product of bounded functions is also a bounded function. The reverse is also valid.

In this system, the second output (that is of course bounded by the reference) is the sum and product composition of state variables (20):

$$h_2 = \left(l_1 i_d + l_2 i_f + l_3 \phi_D\right)^2 + \left(l_4 i_q + l_5 \phi_Q\right)^2 \tag{20}$$

Because the first output h_1 is ω, and it is also bounded by the reference, all state variables are included and it can be concluded that all internal dynamics are bounded.

To achieve global stability, decoupling matrix G has to be globally invertible. Its determinant is (21):

$$Det(G) = m_1 i_d \phi_d + m_2 i_q \phi_q - m_3\, \phi_d^2 - m_4\, \phi_q^2 \tag{21}$$

According to the motor parameters given in the next paragraph (21) becomes (22).

$$Det(G) = 7.11 i_d\, \phi_d + 7.11 i_q\, \phi_q - 34.3\, \phi_d^2 - 50.8\, \phi_q^2 \tag{22}$$

It is not possible to eliminate the first two members in (21), (22) and to theoretically claim global stability, but in all control demands described in the following paragraphs, the determinant always remains far from singularity.

3. Simulation Model

Previous considerations are outlined in the control scheme shown in Fig. 1.

At first, it is necessary to do Park transformation to current and voltage measurements. The adaptive observer then computes all observed states and parameters. Taking

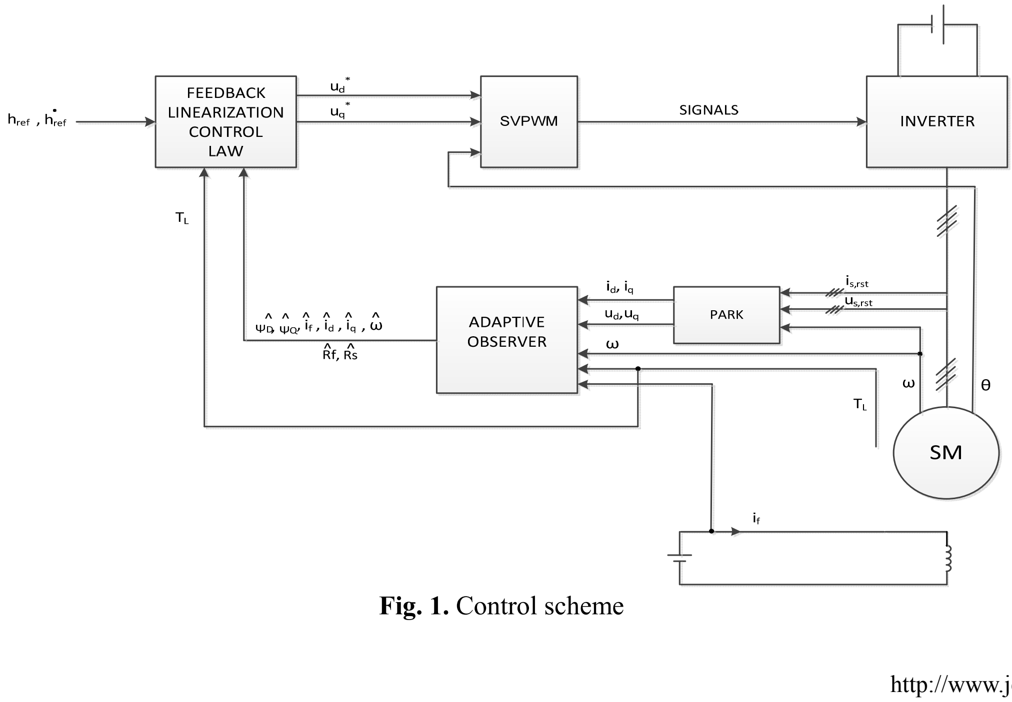

Fig. 1. Control scheme

into consideration references and observed values, the feedback linearization control law calculates reference voltages. Signals for inverter control are then generated by modulation technique. Modulation is done by space vector pulse width modulation (SVPWM). Symmetrical pattern with a switching frequency of 3 kHz is used. The sampling time of the discretized control system is 12 kHz.

At the output of the voltage source inverter (VSI) an RLC filter is typically used. In this study some standard filter values are taken.

Simulations are done by either variable-step of fixed-step solvers. Various precision levels according to step size and tolerances can be set.

The system is usually described in Per Unit System values, and so this system will be used in this case too.

Nominal parameters of the SM are given as Per Unit values on the SM's stator basis; it will be necessary to calculate excitation voltage and reactor inductivity on the same basis.

SM nominal values of power, voltage, frequency, pole pairs and inertia constant are:

$$S_n = 8{,}1 \text{ kVA}, U_n = 400 \text{ V}, f_n = 50 \text{ Hz}, p=2, H = 0{,}1406 \text{ s}.$$

Stator winding (p.u.) values are:

$$r_s = 0{,}082, L_\sigma = 0{,}072, L_{md} = 1{,}728, L_{mq} = 0{,}823.$$

Excitation winding (p.u.) values are:

$$r_f = 0{,}0612, L_{\sigma f} = 0{,}18.$$

Damper winding (p.u.) values are:

$$r_D = 0{,}159, L_{\sigma D} = 0{,}117, r_Q = 0{,}242, L_{\sigma Q} = 0{,}162.$$

Filter reactor (p.u.) value is: $L_{react} = 0{,}158$.

4. Control with Full Order Observer

The results are given in the following figures. They show very accurate performance during the speed reversing process (Fig. 2 - rotor speed, Fig. 3 - rotor speed error). The square of stator flux is also accurately controlled (Fig. 4 - square of stator flux, Fig. 5 - square of stator flux

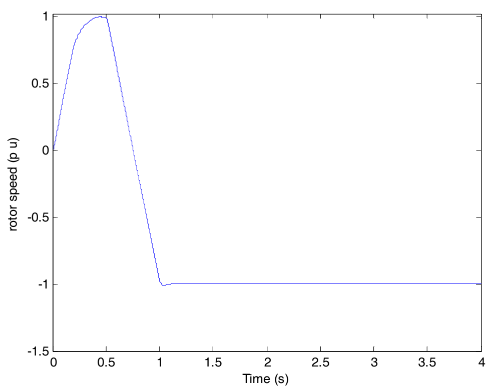

Fig. 2. Rotor speed

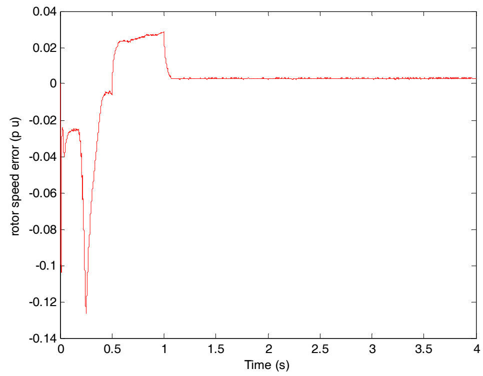

Fig. 3. Rotor speed error

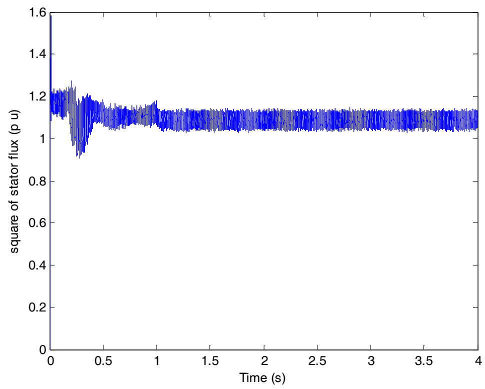

Fig. 4. Square of stator flux

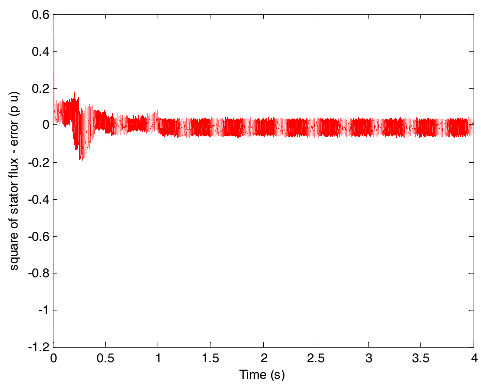

Fig. 5. Square of stator flux error

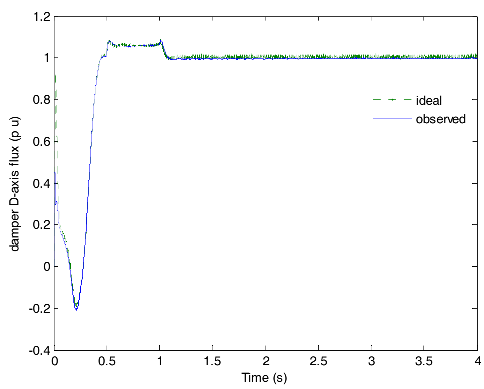

Fig. 6. Damper D-axis flux

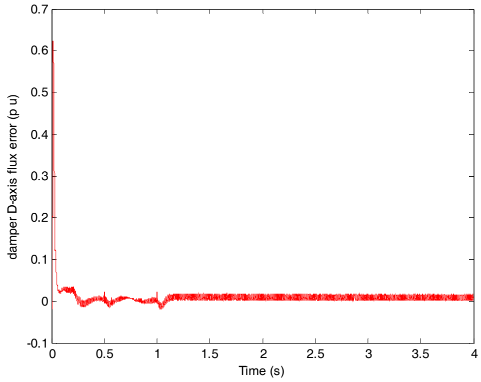

Fig. 7. Damper D-axis flux error

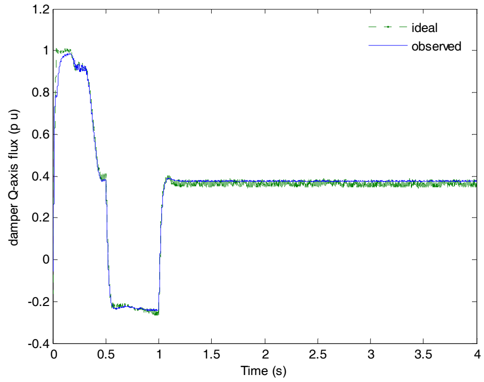

Fig. 8. Damper Q-axis flux

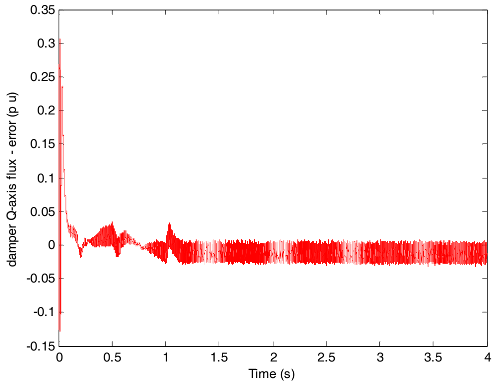

Fig. 9. Damper Q-axis flux error

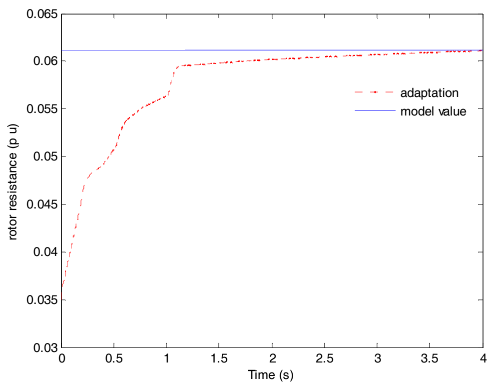

Fig. 10. Rotor resistance adaptation

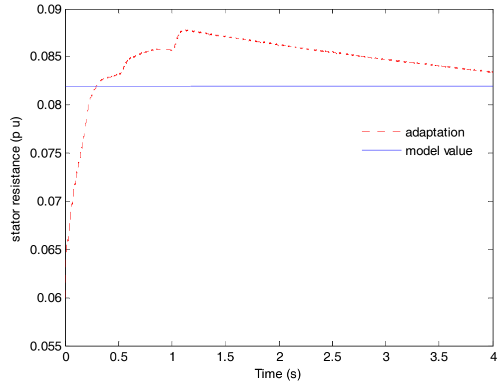

Fig. 11. Stator resistance adaptation

error). The flux observer also gives accurate results. Fig. 6 shows observed and ideal value of damper D axis flux and Fig. 7 shows its observation error. In Figs. 8 and 9 the corresponding values in Q axis are shown. Although resistance adaptability has to be checked in the experiment; in this simulation initial values are set far from the SM model values and, as expected, they approach to the constant model values (Figs. 10 and 11).

5. Control with Reduced Order Observer

Although the results obtained by full order observer are very accurate, an observer still has certain complexity and more importantly it needs load torque knowledge to obtain high level accuracy.

If the reduced order observer is used it is possible to overcome these obstacles. The observer (8) is simple, it does not need voltage measurements and load torque estimation scheme (Fig. 12.) can be implemented.

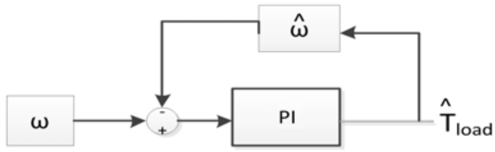

Fig. 12. Load torque estimator

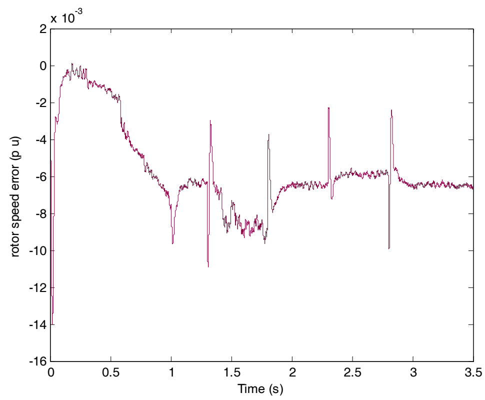

Fig. 13. Rotor speed error

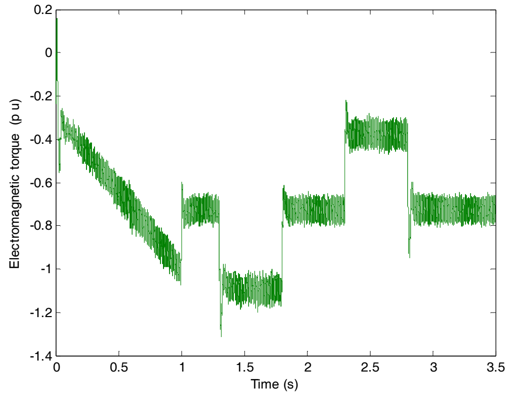

Fig. 14. Electromagnetic torque

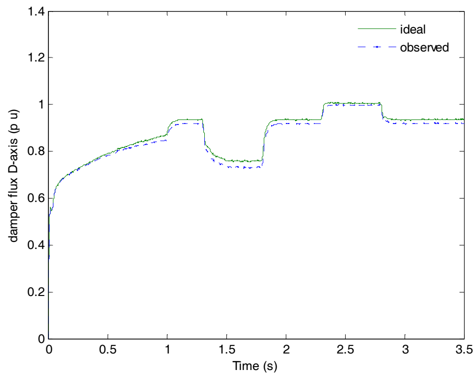

Fig. 15. D-axis flux-comparison

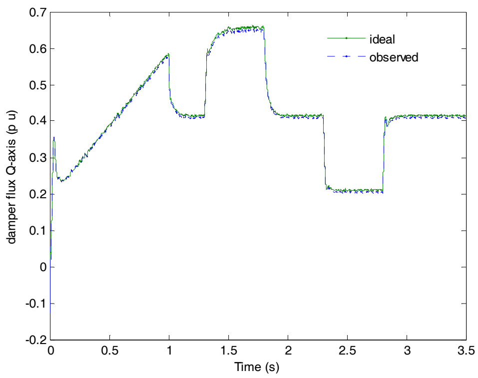

Fig. 16. Q-axis flux-comparison

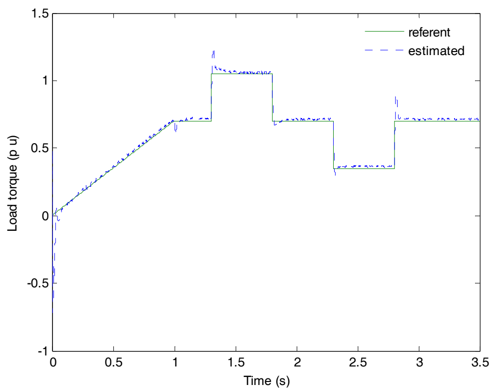

Fig. 17. Load torque-comparison

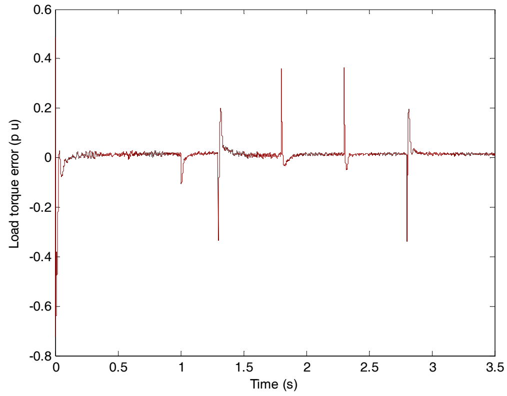

Fig. 18. Load torque estimation error

The estimator contains rotor speed calculation according to the rotor speed dynamics given in (23).

$$\dot{\hat{\omega}} = g_1 i_d i_q + g_2 i_f i_q + g_3 i_q \hat{\phi}_D + g_4 i_d \hat{\phi}_Q + g_5 \hat{T}_L \qquad (23)$$

To check the control's performance, load torque step up and step down changes (after the motor starting) have been simulated. Once again, the simulation results indicate very accurate performance. In Figs. 15 and 16 flux components are given. Estimated load torque (Fig. 17) and its error (Fig. 18) show accurate performance. As a result of the aforementioned, load torque changes have not had an impact on the tracking system; Fig. 13 gives rotor speed error while Fig. 14 gives electromagnetic torque.

6. Comparison Between Linear and Novel Control

The comparison has been done under identical conditions with both systems being in the same simulation model with the same settings. Identical simulation model blocks and parameters are used in both systems. The only difference is the control law block. In the linear control system, instead of the feedback linearization control law given and explained in the previous paragraphs, linear vector control law is implemented. It contains two loops (Fig. 19): the first for flux control that has one PI controller, and the second for speed control that has two PI controllers (one for speed and one for toque control). As in typical vector control, flux is controlled by d-current component

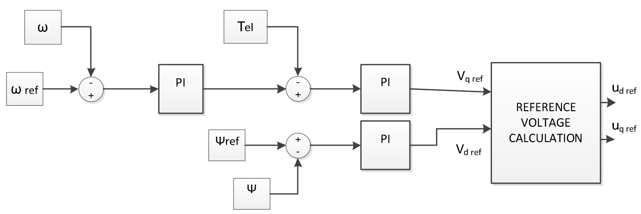

Fig. 19. Vector control scheme

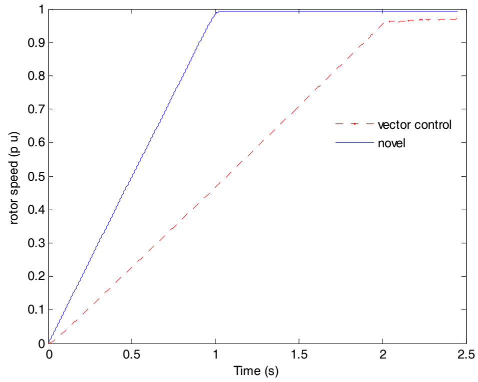

Fig. 20. Rotor speed

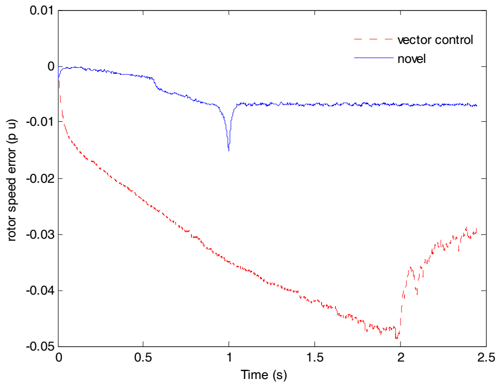

Fig. 21. Rotor speed error

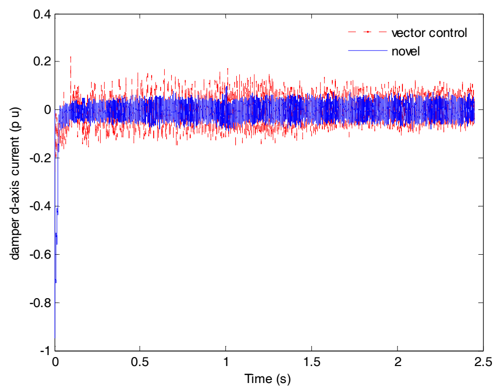

Fig. 22. D-axis damper winding current

and speed is controlled by q-current component.

Reference voltage calculation is done according to simplified dynamics given in (24).

$$\begin{bmatrix} u_d^{ref} \\ u_q^{ref} \end{bmatrix} = \begin{bmatrix} v_d^{ref} - \omega\phi_q \\ v_q^{ref} + \omega\phi_d \end{bmatrix} \tag{24}$$

The results given in the following figures show degraded efficiency of vector control, as expected. In the following figures, the results of nonlinear control are blue colored solid line while the vector control results are in red colored

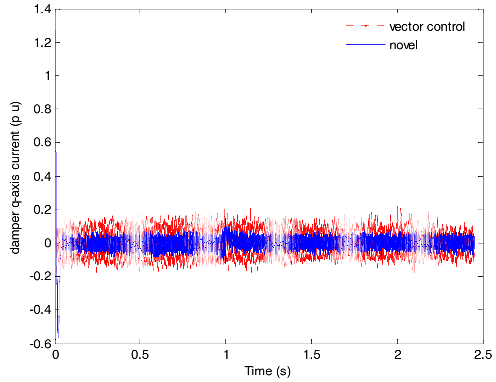

Fig. 23. Q-axis damper winding current

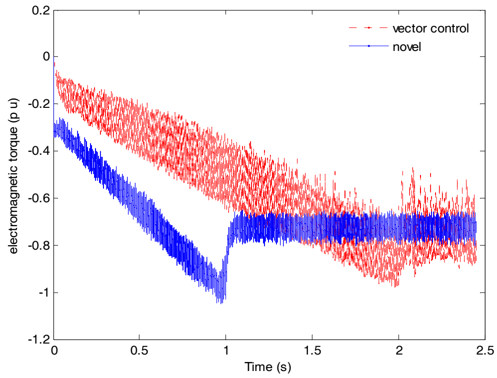

Fig. 24. Electromagnetic torque

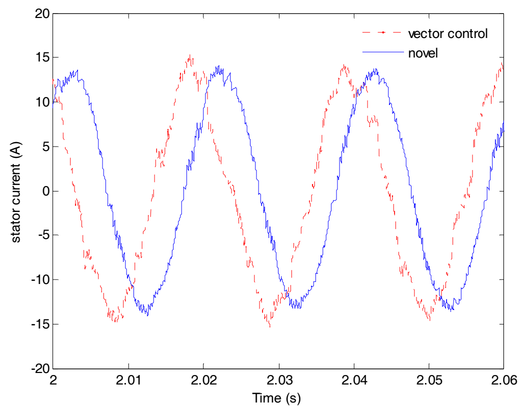

Fig. 25. Stator winding currents

dot line. For the same dynamics the vector control (loaded starting) lasts twice as long (Fig. 20), has higher errors (Fig. 21) and (because of a lesser degree of synchronism) has higher damper windings current oscillations in comparison with the novel control (Fig.(s) 22 and 23). Eliminating damper winding current oscillations by using the novel control law decreases electromagnetic torque ripple (Fig. 24). The current waveforms (Fig. 25), show less harmonic distortion in the novel application. Because of the degraded efficiency, the vector control also needs higher DC voltage then the novel control.

7. Comparison Between Conventional Nonlinear and Novel Control

The vector control principle has been used to form conventional nonlinear control. The normally used vector control principle is to set i_d to zero and to control torque with i_q component. It is according to this principle that backstepping and feedback linearization control laws have been designed.

To make a proper comparison, the novel control has been simulated together with each of the other controls in the same Simulink model, under the same conditions. The starting process with load torque step up at 1,3 seconds and step down at 1,8 seconds has been simulated. The results of the novel control are shown in blue colored solid line while all others are in red colored dot line.

7.1 Backstepping design

Again, the system given in (1) has been used and damper winding has been taken into consideration.

The first step is to define u_d according to the d-current zero reference. Error convergence can be easily achieved and the equation is given in (25).

$$u_d = \frac{\left(-a_1 i_d - a_2 i_f - a_3 i_q \omega - a_4 \phi_D - a_5 \phi_Q \omega - a_6 u_f - k_d e_d\right)}{a_7} \tag{25}$$

where k_d is convergence constant and e_d is d-current error

$$e_d = i_d - i_{dref}.$$

To find the control law for i_q current, a new variable can be defined as (26):

$$\alpha = g_1 i_d i_q + g_2 i_f i_q + g_3 i_q \varphi_d + g_4 i_d \varphi_Q \tag{26}$$

The differential of rotor speed error (e_ω) can be written as (27):

$$\dot{e}_\omega = -k_\omega e_\omega + e_\alpha \tag{27}$$

where k_ω is convergence constant; e_α is the difference between α and its desired value α^* and e_ω is the difference between ω and its refference ω_{ref}.

In the case that desired value of α is α^* (28);

$$\alpha^* = -g_5 T_L + \dot{\omega}_{ref} - k_\omega e_\omega \tag{28}$$

the differential of rotor speed error (e_ω) would be:

$$\dot{e}_\omega = -k_\omega e_\omega \tag{29}$$

and it would be convergent.

According to this analysis Lyapunov fuction can be defined as (30):

$$V_\omega = \frac{1}{2} k_\omega^2 e_\omega^2 + \frac{1}{2} e_\alpha^2 \tag{30}$$

u_q can be obtained regarding Lyapunov function differential (31):

$$\dot{V}_\omega = -k_\omega^3 e_\omega^2 - k_\omega e_\alpha^2 \tag{31}$$

and is given in (32).

$$u_q = \frac{-1}{d_6\left(g_1 i_d + g_2 i_f + g_3 f_D\right)}$$
$$\Big\{\left(a_1 i_d + a_2 i_f + a_3 i_q w + a_4 f_D + a_5 w f_Q + a_7 u_f\right) +$$
$$\left(g_1 i_q + g_4 f_Q\right) + g_2 i_q\left(b_1 i_d + b_2 i_f + b_3 i_q w + b_4 f_D + b_5 w f_Q + b_7 u_f\right) +$$
$$+\left(d_1 i_q + d_2 i_d w + d_3 i_f w f_D + d_5 f_Q\right)\left(g_1 i_d + g_2 i_f + g_3 f_D\right)$$
$$+ g_4 i_d\left(f_1 i_q + f_2 f_Q\right) + u_d\left[a_6\left(g_1 i_q + g_4 f_Q\right) + g_2 b_6 i_q\right]$$
$$-g_5 \dot{T}_L + \ddot{w}_{ref} - 2\dot{e}_w k_w\Big\} \tag{32}$$

The simulation results for the rotor speed and electromagnetic torque are given below: rotor speed (Fig. 26), its error (Fig. 27) and electromagnetic torque (Fig. 28).

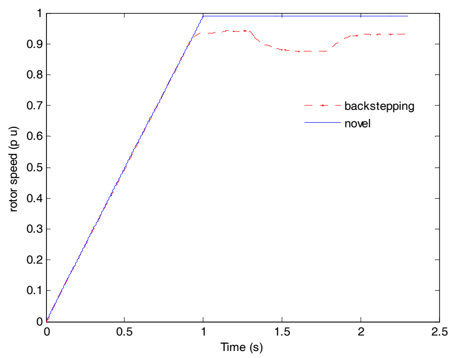

Fig. 26. Rotor speed

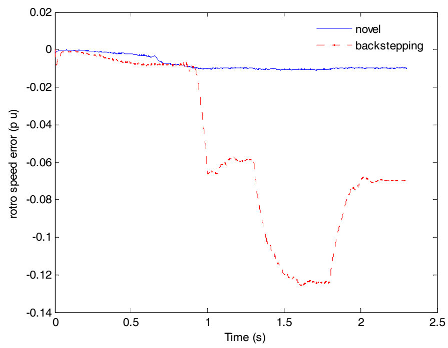

Fig. 27. Rotor speed error

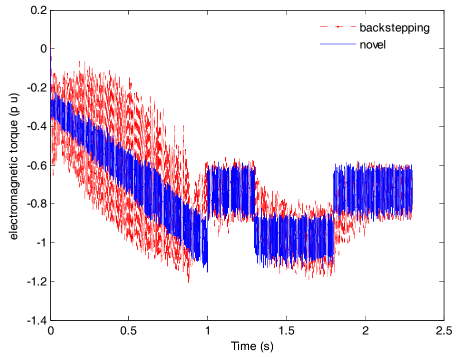

Fig. 28. Electromagnetic torque

Due to torque and flux decoupling in the novel control law, a better use of DC voltage and consequently better performance is achieved. During the starting process, in backstepping control also the high torque ripple appears.

7.2 Feedback linearization without torque and flux decoupling

The vector control principle given in backstepping design has been used again to test the performance of the feedback linearization without torque and flux decoupling control law. The control law for this can be derived similarly to the already given control law (17).

Simulations have been done with and without taking into consideration the damper winding effect.

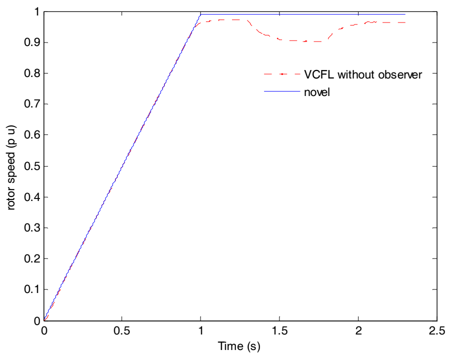

Fig. 29. Rotor speed

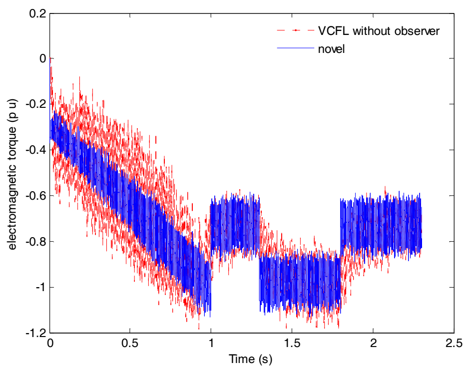

Fig. 30. Electromagnetic torque

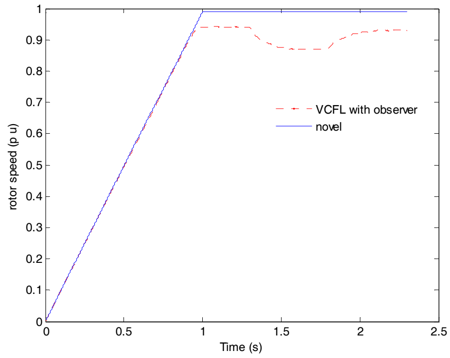

Fig. 31. Rotor speed

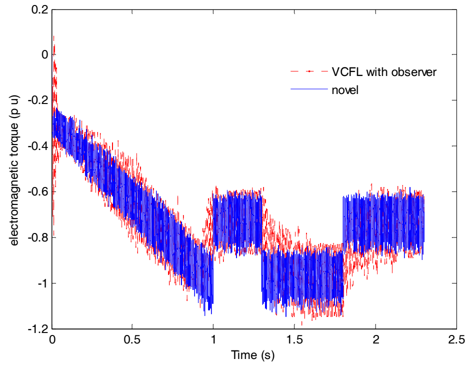

Fig. 32. Electromagnetic torque

The results given in Fig. 29 and Fig. 30 are for the case of damper winding not considered. They show, once again, the same advantages of the novel control as described before.

The feedback linearization with damper winding effect taken into consideration is also given. The advantage of decoupling is once again obvious (Fig. 31) and by taking into consideration the damper winding, the electromagnetic torque ripple will be reduced during the starting process as given in Fig. 32.

8. Conclusion

This paper presents simulation studies of synchronous machine observer-based control. The presented novel control is based on the electromagnetic torque and magnetic flux decoupling principle. To accomplish full decoupling, an observer for the unknown SM states has been used. Full and reduced order observers are also presented.

The method has been checked with the speed reversing tracking system. Comparison of the novel nonlinear control with linear control and also with conventional nonlinear control has been given.

Simulation results show that precise control has been achieved. It is shown that decoupling enables much better use of DC voltage, while the use of damper winding observer reduces torque ripple. These two contributions incorporated together into the control system enhance performance and operational range of SM drives.

The control system is discretized and thus the sample data system has been defined. From Simulink blocks, the control system is easily convertible to C-code and is being prepared for DSP implementation.

The method can also be used for torque control, in both motor and generator operation regimes, and can be applied to any kind of synchronous machine including permanent magnet synchronous machines.

Synchronous Machine Parameter and State Symbols

L_{md} – d-axis mutual inductance
L_d – stator d-axis inductance
L_σ – stator leakage iductance
L_D – damper d-axis inductance
$L_{\sigma D}$ – damper d-axis leakage inductance
L_f – field inductance
$L_{\sigma f}$ – field leakage inductance
L_{mq} – q-axis mutual inductance
L_q – stator q-axis inductance
L_Q – damper q-axis inductance
$L_{\sigma Q}$ – damper q-axis leakage inductance
r_s – stator resistance
r_f – field resistance
r_D – damper d-axis resistance
r_Q – damper q-axis resistance
H – inertia constant
i_d – stator d-axis current
i_f – field current
i_q – stator q-axis current
φ_D – damper d-axis flux
φ_Q – damper q-axis flux
φ_d – stator d-axis flux
φ_q – stator q-axis flux
ω – rotor speed
T_L – load torque

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