Modeling and Sensorless Control of a Permanent Magnet Generator Based on an Adaptive Estimator Scheme

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Abstract. Recently, several sensorless control technologies have been employed in industrial systems due to the ability of these technologies to estimate uncertain parameters and inaccessible measurements. Furthermore, sensorless technology reduces complexity and thus reduces costs, as well as providing higher reliability than traditional sensors in markets. This study proposes an efficient controller that controls a variable speed of permanent magnet generator based on an adaptive estimator scheme under uncertain armature resistance and unknown generator torque. The proposed scheme estimates the uncertain parameters and state variables of the system, which provides accurate assessment for feedback control. This research paper takes into consideration the combination of inter sampled concept, time delay due to electrical time constant and high gain approach, although these are not specifically discussed, yet according to our knowledge. The proposed estimator is robust against sampling interval, time delay and it can instantaneously access the output state variable to solve the problem of estimation processes under some persistent excitation conditions. The proposed estimator has been tested with a sensorless controller applied to a 5.5 kW variable speed permanent magnet generator. The proposed controller plays an active role in creating a compromise solution between the sampling time of 1.5 ms and the time delay of 10 ms with appropriate design parameters. Simulink model and the corresponding practical connection of sensorless control technology based on an adaptive estimator scheme have been done, successfully.

List of Abbreviations:

| Abbreviation | Description |
|--------------|-------------|
| PMG          | Permanent magnet synchronous generator |
| MAST         | Maximum allowable sampling time |
| MATD         | The maximum allowable time delay |
| PWM          | Pulse width modulation |
| AC/DC        | AC to DC electronic converter |
| DSP          | Digital signal processing |

1. Introduction

Essentially, permanent magnet generator (PMG) is widely used in the integration of AC systems [1]. The PMG is the most efficient machines. It has a movable magnet inside the rotating part. It needs less routine maintenance and repair because of its robust design. The major challenge in PMG is to control the dynamic torque and rotor speed, which increase nonlinearly in the overall system. Permanent magnet generators (PMGs) are widely used in an integrated form in AC machines. The major challenge in PMG is to control the dynamic torque and rotor speed, both of which increase nonlinearly within the overall system. This nonlinearity occurs according to uncertain parameters, and changes in state variables with or without magnetizing effects. Thus, in order to solve this issue, an adaptive nonlinear estimator-based sensorless control technique is required to avoid additional complexities [2].

Recently, several studies have attempted to employ estimator to overcome the parameter uncertainties inherent in system modeling. This was achieved by authors in [3], who developed an adaptive estimator that operates on continuous-discrete synthesis principles. An adaptive estimator was also developed in [4], based on hybrid estimator design principles. The author in [5] further
provided a nonlinear sensorless control algorithm, which operates sensorlessly to control the variable speed of electrical AC drives without the use of classical sensors.

In general, output feedback control is one of the most common strategies applied to PMGs. This strategy is proposed in several studies, such as in [6]. The designed control strategy is based on a cascade structure for which the inner loop is input controlled by the outer loop to maintain a given reference speed. An output feedback predictive controller, which is adaptive with respect to parameter uncertainties, is thus applied to three–phase induction motors [7 - 8].

The primary focus of the present study is proposing an adaptive nonlinear estimator for sensorless measurements that are designed to simultaneously estimate the unmeasured mechanical state variables based on the uncertain armature resistance of a PMG for variable rotor speeds. The adaptive estimator uses a highly intuitive gain adaptive dynamic law designed for looking for the optimal armature resistance of the PMG. Online estimations of electro-mechanical states, including rotor velocity and generator torque, taking into account the electrical variables, are used to compute the electromagnetic torque using indirect methods, and thus the input control voltages are accessible to measurement.

This research paper is organized as: Section 2 describes PMG modeling and outlines the problem statement. Section 3 focuses on the elaboration of the adaptive estimator synthesis and analysis of stability, taking into account delayed and sample measurements. In section 4, feedback controller design is presented, whilst section 5 presents the simulation results and verifications applied to the variable speed PM synchronous generator. This performance of the proposed approach in terms of the mathematical model is discussed. Finally, the conclusions and remarks are provided in section 6.

2. PMG model and Problem Statement

2.1 Reduced Model of PMG

The PMG system model is presented in terms of \((\alpha-\beta)\) coordinates. It should be clarified that the dynamics of generator torque are considered to be an uncertainty function, \(\varepsilon(t)\). The main equations of such systems are shown below [8]:

\[
\begin{align*}
\sum \text{Full Model} & \begin{cases}
\frac{di_g}{dt} = -\frac{R_a}{L_a}i_g - \frac{p}{L_a}\omega_g H\psi_r - \frac{1}{L_a}u_g \\
\frac{di_r}{dt} = p a_p H\psi_r \\
\frac{d\omega_g}{dt} = -\frac{1}{J_g} i_g^T H\psi_r - \frac{f_c}{J_g} \omega_g + \frac{1}{J_g} T_g \\
T_g = \varepsilon(t)
\end{cases}, \quad \in \mathbb{R}^6
\end{align*}
\]

where, \(i_g \equiv col(i_{gα}, i_{gβ}), \psi_r \equiv col(\psi_{rα}, \psi_{rβ}), u_g \equiv col(u_{gα}, u_{gβ})\) are the currents of the stator vector, the leakage fluxes, and the input control of the generator, respectively. The states \(\omega_g\) and \(T_g\) denote the generator rotor speed and the torque, respectively, both of which have unknown values. \(H \in \mathbb{R}^2, H \equiv [0 \quad -1; 1 \quad 0], J\) and \(f_c\) are generator inertia and friction, respectively, and \(p\) represents the pole pairs. The parameters \(R_a\) and \(L_a\) are the stator resistor and winding inductance, respectively. The electromagnetic torque can also be assessed using first term of the third subsystem in (2). The PMG can be reformulated in a reduced model to minimise the complexity of system calculations, however:

\[
\begin{align*}
\sum \text{Reduced Model} & \begin{cases}
\dot{\omega}_g = \frac{\tau_{em}}{J} - f_c \omega_g + \frac{1}{J} T_g \\
\dot{T}_g = \varepsilon
\end{cases}, \quad \in \mathbb{R}^3
\end{align*}
\]

The above model can then be further re-formulated using the adaptive version by considering the fact that \(\tau_{em}\) is inaccessible for measuring, and can only be sampled; this data can thus be considered as \(\tau_{em}(t_k)\), where \((k = 0,1,2, \ldots)\), and the model is thus written as

\[
\sum \text{Extended Model} \begin{cases}
\dot{x} = F(i_g, \psi_r)x + G(x, u_g) + A(x, \psi_r, i_g) R_a + \varepsilon \\
\hat{R}_a = 0 \\
y(t_k) = Cx(t_k) = x_1(t_k) = \tau_{em}(t_k)
\end{cases}
\]

where the column vector \(x \triangleq (x_1, x_2, x_3)^T \triangleq (\tau_{em}, \omega_g, T_g)^T\).
\[ F(g, \psi_r) \equiv \begin{pmatrix} 0 & -\gamma_2(g, \psi_r) & 0 \\ 0 & 0 & \frac{1}{T} \\ 0 & 0 & 0 \end{pmatrix} \in \mathbb{R}^{3 \times 3}, \quad G(x, u_g, \psi_r) \equiv \begin{pmatrix} -\frac{\xi}{s} - \frac{a}{s^2} & 0 \\ -\frac{a}{s^2} & 0 \end{pmatrix}, \quad C = [1 \ 0 \ 0], \in \mathbb{R}^3 \]

and, \( \Sigma \equiv [0 \ 0 \ e]^T \), \( \Lambda(x, \psi_r, i_g) \equiv \begin{bmatrix} \gamma_1(\psi_r, i_g) & \gamma_2(x_2, \psi_r, i_g) & \gamma_3(x_3, \psi_r, i_g) \end{bmatrix} \in \mathbb{R}^3 \)

2.2 System Construction in z Benchmark

Considering the system model as constructed in z benchmark after a change of coordinates (i.e., \( x \rightarrow z \)). This scenario used for putting the system model in observable normal form.

\[ \Sigma \text{ benchmark} \left\{ \begin{array}{l}
\dot{z} = Az + \phi(z, u_g) + \Lambda(x, \psi_r, i_g) R_a + b(z) \Sigma \\
y(t_k) = C z(t_k) = z_1(t_k) = T_{em}(t_k)
\end{array} \right. \] (4)

\[ \begin{aligned}
\dot{z}_1 &= z_2 + \varphi_1(z, u_g) + \gamma_1(\psi_r, i_g) R_a \\
\dot{z}_2 &= z_3 + \varphi_2(z, u_g) + \gamma_2(x_2, \psi_r, i_g) R_a \\
\dot{z}_3 &= \varphi_3(z, u_g) + \gamma_3(x_3, \psi_r, i_g) R_a + b(z) \Sigma
\end{aligned} \] (5)

and \( \varphi_1(z, u_g) = \gamma_1(i_g, u_g, \psi_r) = \frac{\gamma_1}{l_a} (\psi_{ra} u_{ga} - \psi_{r\beta} u_{g\beta}), \quad \varphi_2(z) = -\frac{\gamma_2}{l_a} (\psi_{ra} u_{ga} - \psi_{r\beta} u_{g\beta}) \), \( \varphi_3(z) = -\frac{3}{l_a} x_2 (\psi_{r\beta}^2 - \psi_{r\beta}^2) \)

and,

\[ \varphi_3(z) = \frac{x_3}{l_a} \left[ -1.5 p^2 \left( -p x_2 \psi_{r\beta} i_{ga} + \psi_{ra} \left( \frac{p}{l_a} \psi_{r\beta} - \frac{1}{l_a} u_{ga} \right) \right) + \frac{3}{l_a} p^2 x_2 \left( \psi_{r\beta}^2 + \psi_{r\beta}^2 \right) \right] \]

with, \( \Lambda(x, \psi_r, i_g) \equiv \begin{bmatrix} \gamma_1(\psi_r, i_g) & \gamma_2(x_2, \psi_r, i_g) & \gamma_3(x_3, \psi_r, i_g) \end{bmatrix} \)

and \( \Lambda(x, \psi_r, i_g) = \begin{bmatrix} \frac{1.5 p}{l_a} (\psi_{ra} i_{ga} - \psi_{r\beta} i_{g\beta}) \\ \frac{1.5 p^2}{l_a} i_{g\beta} \psi_r x_2 \\ \frac{1.5 p^2}{l_a} i_{g\beta} \psi_r x_3 \end{bmatrix} \) (6)

3. Adaptive Estimator Design and Stability Analysis

3.1 Adaptive Estimator Synthesis

In this subsection, an adaptive estimator is suggested of the form \( \forall k \in \mathbb{N}, \forall t \in [t_k + \tau, t_{k+1} + \tau] \). A simple comparison with latest published results, such as with third class of nonlinear system given in [9], suggests that the use of an adaptive estimator does not take into consideration the influence of unknown disturbances.

On another hand, the authors in [10] focused on linear systems and did not apply inter-sample behaviors. Instead, an auxiliary variable, \( \lambda \), was seen to play a crucial role in the convergence of uncertain parameters, which was also remarked on and provided by [11], again without considering the principal of sampled and delayed measurements in estimator construction.

Thus, the model of the proposed estimator that takes into consideration sampled and delayed measurements is clarified in (7). It has sixth order system dynamics:

\[ \dot{\hat{x}} = A \hat{x} + \varphi_0(\hat{x}, u_g) + \Lambda(\hat{x}, \psi_r, i_g) R_a - S^{-1} C^T(C \hat{z}(t - \tau) - w) \] (7a)
Adaptive Estimator

\[
\begin{align*}
\dot{R}_a &= -\Gamma(t)T^TC\hat{z}(t - \tau) - w \\
\dot{\lambda} &= \left(A - S^{-1}C^TC\right)\lambda + \Lambda(\xi, \psi, i_g) \\
\dot{S} &= -\theta_m S - SA - \dot{\lambda}^2 S + C^TC \\
w(t_k + \tau) &= y(t_k)
\end{align*}
\]

where \( \hat{z} \in \mathbb{R}^3 \) and \( \hat{R}_a \) are the estimates of the states and unknown parameter, respectively. The matrix \( \Gamma(t) \in \mathbb{R}^{n \times m} \) is a positive definite matrix that represents a solution of the third subsystem in (7), while \( \lambda(t) \in \mathbb{R}^{n \times e} \) is the solution of the fourth subsystem of (7), where \( S \) is a symmetric positive definite matrix. This allows for a proof that the proposed estimator given in (7) is an exponential convergence for the model given in (4) when accompanied by sampled and delayed measurements. Figure (1) shows full details of the sensorless control based adaptive scheme. The prime movers for PMG may be gas, steam or wind turbines.

Table 1 briefly summarises the pros and cons of the estimator topologies that is given in [15] and the proposed estimator in the current study. In this table, one topology, the extended nonlinear estimator, seems \textit{a priori} more exploitable for online estimation. Indeed, this estimator provides good options for sensorless control without resorting to the use of mechanical or other classic sensors.

From the second remark given in [12], PMG is observable in the rank sense, and it has been emphasized that the norm of the rotor flux is constant and never vanishes. Practically, the concept of observability is lost only at the singular point corresponding to zero speed.

3.2. Stability Analysis

\textbf{Theorem} (Main result): The system model, as clarified by the set of differential equations, is defined in (4) and the adaptive estimator is defined in (7). This leads to a derivation of a maximum sampling period, \( T_{\text{MSP}} \), and a maximum timing delay, \( T_{\text{MATD}} \), using the Lyapunov stability technique as in the following

\[
T_{\text{MSP}} \geq \frac{\theta_m}{\bar{\alpha}_1 + 1 + \|CA\|\|\theta_m + \Lambda(\xi, \psi, i_g)\| + \theta_m^2 + \|C\beta_0\|\theta_m^2 + 4\|C\|^2\theta_m^2}{\bar{\alpha}_1\exp^{-\frac{\bar{\alpha}_1 t}{2}}}
\]

and

\[
T_{\text{MATD}} < \min \left\{ \frac{1}{\bar{\alpha}_2 \theta_m + 2\bar{\alpha}_1 \theta_m \alpha_2 \|C\beta_0\| + 2\|C\|^2 + 2\bar{\alpha}_1 \|CA\|\theta_m + m + \frac{4\|C\|^2}{\bar{\alpha}_2 \exp^{-\frac{\bar{\alpha}_2 t}{2}}}} \right\}
\]

Let \( \theta(t) \) is a piecewise differentiable positive function designed for the purpose of correcting the error between the predictor and the output signal such that, \( \theta(t) \) submits to the following conditions:

\[
\begin{align*}
\theta(t) &> 0, \forall t > 0 \\
\theta(t_k) &= \theta_m, t_k \in \mathbb{R}^+ \\
\dot{\theta}(t) &< 0, \forall t \in [t_k, t_{k+1})
\end{align*}
\]

The extended adaptive estimator that is given in (7) ensures an exponential convergence for the system model that is given in (4). Consequently, the closed loop trajectories converge asymptotically to the region of attraction with positive tuning parameters. Unfortunately, the proof of the proposed theorem has been removed due to the limitation in a number of words.
| Type | Pros | Cons |
|------|------|------|
| Extended Nonlinear Adaptive Estimator | ✓ Suggests a technique for a change of coordinates.  
✓ Possibility to extend the system model, dynamically to provide estimator normal form.  
✓ The output state is injected to a nonlinear term of the estimator.  
✓ The general structure of the estimator is based on a high gain estimator.  
✓ Used to estimate online unmeasured variables based on input/output measurements.  
✓ Robust with parametric uncertainties. | ✓ Output could be linearized resulting in loss of estimation accuracy.  
✓ The generator torque is a constant function and its dynamics =0.  
✓ The estimator is based on input/output injection measurements in continuous time mode.  
✓ Rapid transients affect the estimation.  
✓ Errors converge asymptotically.  
✓ Requires persistent excitation input.  
✓ Requires discretization for implementation.  
✓ Inter-sample behavior is null.  
✓ Not very robust for sampling schedule.  
✓ Diverges near un-observability region. |
| Sampled and Delayed Output Estimator (current study) | ✓ Suitable for a class of MIMO nonlinear systems disturbed by generator loads.  
✓ Enjoy sampled and delayed output nature.  
✓ Combines the benefits of high gain nature and inter-sample behavior.  
✓ State estimation and output prediction errors vanish exponentially.  
✓ The generator torque is an unknown bounded function, so can be used in practical cases.  
✓ The inter-sample technique is reinitialized impulsively whenever data are available.  
✓ The output data measurements are inaccessible modes, used only at the sampling instant. Used to estimate unmeasured state variables based on armature voltage measurements.  
✓ Sampled output measurements are much more suitable in industrial process and those data can be transmitted using DSP technique.  
✓ Robust, with sampling and time delay schedules.  
✓ No sensitivity to parametric uncertainties. System model is uniformly observable. | ✓ There are no cons, to our knowledge |
4. Sensorless Feedback Controller Design

As the controller is generally designed using the direct - quadrature model which necessitates for online measurements of several state variables, two control inputs, \( u_d \) and \( u_q \), are required for the system to compute \( i_d \) and \( i_q \) after doing the inverse Park transformation. The electronic converter features in terms of the fact that the generator stator \( d \) and \( q \) voltages can be controlled independently. The control objective is to determine under what conditions all computed PMG states \( T_{em} \), \( \omega_g \), and \( T_g \) can be exactly determined in terms of the generated voltage measurements [12]. The model of the PMG in \((d - q)\) reference frame is described by a set of differential equations given in[13]:

\[
\Sigma_{d-q} = \begin{cases} 
\frac{di_d}{dt} = -\frac{R_a}{L_a} i_d + p \frac{L_\psi}{L_a} \omega_g - \frac{1}{L_a} u_2 \\
\frac{di_q}{dt} = -\frac{R_a}{L_a} i_q + p \frac{L_\psi}{L_a} \omega_g - p \omega_g i_d - \frac{1}{L_a} u_1 \\
\frac{d\omega_g}{dt} = -1.5 \frac{L_\psi}{J} \psi_r i_q - \frac{L_\psi}{J} \omega_g + \frac{1}{J} T_g
\end{cases}
\]

(10)

4.1 Rotor Speed Regulator
Step 1: Define the speed tracking error [1] as $E_1 \equiv \omega_y - \omega_{ref} \equiv \xi_1 - \delta_0$
where $\omega_{ref}$ is the speed reference and $\delta_0$ is first virtual control function,
$$E_1 = \omega_y - \omega_{ref} = \xi_1 - \delta_0$$
Equation (11)

From the closed loop system (1), substituting into (11) gives
$$\dot{E}_1 = \frac{p}{J} \psi_r i_q - \frac{p}{J} \omega_y + \frac{E_1}{J} \omega_{ref}$$
Equation (12)

Suppose $E_1 \equiv \xi_2 + \mu_1 = \dot{\omega}_y$ with $\xi_2 = \frac{p}{J} \psi_r i_q$ and $\mu_1 = \frac{E_1}{J} \omega_{ref}$

Let us choose first,
$$W_1(E_1) \equiv \frac{1}{2} E_1^2$$
Equation (13)

Defining the second virtual control as
$$\delta_1 \equiv -\alpha_1 E_1 - \mu_3$$
Equation (14)

Defining $E_2 \equiv \xi_2 - \delta_1$, where $\delta_1$ is the second virtual stabilization function thus gives
$$\dot{E}_2 = \xi_2 - \delta_1$$
Equation (15)

Thus, the time derivative of $W_1$ is:
$$W_1 = E_1 \dot{E}_1 = E_1(E_2 - a_1 E_1^2)$$
Equation (16)

Step 2: Considering the following error $E_2 \equiv \xi_2 - \delta_1$, it follows that
$$\dot{E}_2 = \dot{\xi}_2 - \dot{\delta}_1$$
Equation (17)

(12) and (14) can be substituted into (18), giving
$$\dot{E}_2 = \frac{p}{J} \psi_r i_q - \delta_1 = \frac{p}{J} \psi_r \left(-\frac{R_a}{L_s} i_q - p \omega_y i_d \right) - \frac{1}{J} \psi_r u_i$$
Equation (19)

and,
$$u_2 = \frac{p}{J} \psi_r \left(-\frac{R_a}{L_s} i_q - p \omega_y i_d \right) - \frac{1}{J} \psi_r u_i$$
Equation (20)

Defining the augmented Lyapunov candidate function, it gives
$$W_2(E_1, E_2) \equiv W_1(E_1) + \frac{1}{2} E_2^2$$
Equation (21)

The time derivative along the closed loop trajectory is thus:
$$W_2(E_1, E_2) = W_1(E_1) + E_2 \dot{E}_2 = -a_1 E_1^2 + E_1 E_2 + E_2 \dot{E}_2$$
Equation (22)

To enforce the stability convergence of PMG, the $q$-axis input control signal can be computed from (22) based on the PWM technique seen in [13]:
$$u_1 = \frac{1}{K} \left[ -a_2 E_2 - \mu_2 - E_1 \right]$$
Equation (23)

or,
$$u_1 = \frac{1}{K} \left[ -a_2 E_2 - \frac{p}{J} \psi_r \left(-\frac{R_a}{L_s} i_q - p \omega_y i_d \right) - \left(-a_1 \dot{E}_1 - \mu_3 \right) - \left(\omega_y - \omega_{ref} \right) \right]$$
Equation (24)

4.2 Direct Axis Current Regulator

Step 3: Optimisation of the direct axis current [12], $i_d = \dot{d} = 0$. ($i_d$ tracking error)
$$E_3 \equiv \xi_3 - \delta_2 = i_d - i_{dref} \text{ and } \dot{E}_3 = \dot{i}_d - i_{dref} = \frac{R_a}{L_s} \dot{i}_d + p \omega_y i_q + \frac{1}{L_s} u_2$$
Equation (25)

The augmented Lyapunov function candidate is thus
$$W_3(E_3) \equiv \frac{1}{2} E_3^2 \equiv \frac{1}{2} \dot{i}_d^2 \text{ and } W_3 = E_3 \dot{E}_3 = u_i i_d = i_d \left(-a_3 \dot{i}_d - \frac{R_a}{L_s} \dot{i}_d + p \omega_y i_q + \frac{1}{L_s} u_2 \right)$$
Equation (26)

Consequently, the second control input control signal is
$$u_2 = \left(-a_3 L_s + \frac{R_a}{L_s} \right) i_d - p \omega_y L_s i_q$$
Equation (27)

with $a_1, a_2, a_3 > 0$ as positive design parameters, $\psi_r$ is considered rotor flux constant for PMG.

4.3 Sensorless Feedback Technology

The high cost and unreliable sensors involved in the control laws defined by (23) and (26), can thus be replaced by the online estimates provided by the proposed estimator. Finally, the sensorless controller can be designed using a set of adaptive control laws based on PWM technique [14].
\[
\begin{align*}
\hat{u}_1 &= \frac{1}{L_s} \left[ -a_2 E_2 - \frac{2}{p} \psi_m \psi_{pm} \left( -\frac{R_a}{L_s} i_q - p \omega_g i_d \right) - \delta_1 - (\omega_g - \omega_{ref}) \right] \\
\hat{u}_2 &= \left[ (-a_3 L_s + R_a) E_3 - p \omega_g L_s i_q \right]
\end{align*}
\]
(27)
(28)

These voltages can also be presented in terms of the switching control action [5]:
\[
\hat{u}_q \triangleq \hat{u}_d V_{dc}, \quad \hat{u}_d \triangleq \hat{u}_q V_{dc}
\]
where, \( \hat{u}_q \) and \( \hat{u}_d \) show the average \( (d-q) \) axis of the three-phase duty ratio system \((Q_a, Q_b, Q_c)\) as
\[
Q_i \triangleq \begin{cases} 
1 & \text{if } Q_i \text{ ON and } \bar{Q}_i \text{ OFF} \\
0 & \text{if } Q_i \text{ OFF and } \bar{Q}_i \text{ ON} 
\end{cases} 
\quad i = a,b,c
\]
such that
\[
V_{ab} \triangleq (Q_a - Q_b)V_{dc}, V_{bc} \triangleq (Q_b - Q_c)V_{dc}, V_{ca} \triangleq (Q_c - Q_a)V_{dc}
\]
(30)

5. Simulation Results and Verification

The behavior of the suggested model was tested in terms of rotor speed, generator torque, electromagnetic torque and uncertain armature resistance. Table 2 shows the mechanical and electrical data obtained from the simulated model. The system model is given in (2) and the proposed estimator was accomplished using realistic benchmark MATLAB and Simulink resources version R2016/ Sim power system. The dynamic response was checked by means of the simulation values provided within the scheme design parameters, sampling interval, and required timing delay. A computer flowchart for the simulated case study is shown in Figure 2.

Simulink model and the corresponding practical connection of sensorless control technology based on an adaptive estimator scheme were illustrated in Appendix A. To validate the robustness of the proposed adaptive estimator, the test benchmark includes some limited cases which are generator torque profile is starting from zero and slow variations. Figure 3 (a) clarifies generator torque profile provided by prime mover measured in (N.m) and Figure 3(b) involves rotor speed profile measured in (rad/sec). Also, time variations of generator torque and rotor speed profiles are taken into its consideration.

5.1 Adaptive Estimator Dynamic Performance

A summary of results for the parameters of the proposed adaptive estimator is listed in Table 3. It is highly recommended that the gain parameter should be selected as a compromise solution between a suitable convergence and sensitivity of the proposed estimator. The initial boundaries of the matrices, namely \( S(t), \Gamma(t) \), are set to \( S(0) = I_3 \) and \( \Gamma(0) = I_3 \), where \( I_3 \in \mathbb{R}^{3x3} \). One solution of the Lyapunov equation is thus, \( S^{-1}C^T = n/(n+p)I \); \( pl = col \{ C_3^1, C_3^2, C_3^3 \} = col \{ 3, 3, 1 \} \), which is the binomial coefficient. Based on the simulation results and verification, a time delay of 10 ms is enough to avoid a transient state, avoid the influence of electrical time constants, and minimise the initial DC offset. The estimator initial boundaries, \( \hat{\omega}_r(0) \) and \( \hat{T}_g(0) \), can be arbitrarily chosen to prove the capability of the proposed estimator design.

The estimator's dynamic performances are illustrated in Figures 3 and 4. They clarify the comparison waveforms for the dynamic tracking performances of the proposed estimator as being satisfactory in terms of PMG real and estimated variables. However, as expected, the rapid transient nature of generator torque with timing delay affects the estimation activity, instantaneously.

This state is interpreted through the occurrence of sudden disturbances in generator torque and rotor speed as shown in Figure 3 (c) and Figure 4 (d) at time 25 s of the complete cycle. Figure 4 (e) clarifies real and estimation of uncertain armature resistance that ensures robustness the proposed estimator with parametric uncertainties. It is evident from simulation results that the proposed adaptive estimator enters the steady state region with settling time \( \leq 30 \) msec.

5.2 Sensorless Feedback Control

The control design parameters are listed in Table 3. Figure 4 (f) involves a \( d \)-axis current optimization created using a backstepping design technique. Figure 5. (g) shows first \( q \) – axis input control signal
that is given in (27), while Figure 5 (h) shows a second d-axis input control signal that is given in (28). These are also accomplished using backstepping design techniques. It is evident that the dynamic performances of control laws are affected by unknown generator torque and rotor speed. These figures are affected by sufficiently white noise. Figure 5 (i) clarifies the DC output across the resistive load. However, the sudden variation of generator torque captured by a prime mover effect on the estimation and prediction process. This state is depicted through the appearance of undershooting ≤ 2 seconds in some of the figures. The simulation results are satisfactory and prove the ability of the sensorless controller in keeping the system output voltage, rotor speed and direct axis current within acceptable levels. Table 4 lists the prices of classical sensors in markets used for state variable measurements in comparison with saving cost in sensorless control technology.

5.3 Sampled Data Measurements

Figure 6 (j) illustrates output prediction error which converges to zero after 0.8 s and Figure 6 (k) shows the online simulate and estimated electromagnetic torque measured in N/m for a complete cycle of 35s. This prediction is an output state variable that is affected by sampled and delayed measurements. These data are much more suitable for industrial process and they can be transmitted using DSP. This is provided by a pulse generator with a specific sampling interval as given in (8).

Table 2. Mechanical and electrical data of the simulated PMG model.

| Three - Phase Electricity | 400 V / 50 Hz |
|--------------------------|--------------|
| AC / DC boost converter  | $V_{DC} = 600 \, V, \, C = 20 \, \mu F, \, R_L = 0.6 \, k\Omega$ |
| Modulation frequency     | $f_m = 10 \, \text{HZ}$ |
| PMG Characteristics      | Rated capacity = 5. 5 kW; Stator resistance = 0.78\Omega; Stator inductance = 7.8 mH, Moment of inertia = 1.3 Nm/ rad / s$^2$ ; Viscous friction = 0.001417 Nm/ rad/ s; Number of pole pairs = 2. |

Table 3. Sensorless control design parameters

| Index          | Value  |
|----------------|--------|
| $\theta_m$    | 105    |
| $T_{MASP}$    | 1.5 ms |
| $\tau_{MATD}$ | 10 ms  |
| $a_1, a_2, a_3$ | 10,113,35 |

Table 4. Prices of classical sensors used for mechanical and electrical measurements.

| Feature               | Tachometer Sensor | Rotary Torque Sensor | Electromagnetic Sensor |
|-----------------------|-------------------|----------------------|------------------------|
| Price                 | Between $ 5 and $ 35 | Between $ 25 - $ 250 | Between $20 - $ 450    |
Figure 2. Computer flowchart for the simulated case study

Figure 3. (a) Torque profile provided by a prime mover in (N. m), (b) Generator rotor speed profile in (rad/sec) (c) Simulated and estimated rotor speed measured in (rad/sec) at \( \tau_{MATD} = 10 \text{ ms} \).

Figure 4. (d) Simulated torque and its estimate measured in N.m, (e) Real and estimation of uncertain armature resistance measured in \( \Omega \) at \( \tau_{MATD} = 10 \text{ ms} \). (f) Optimization of \( d \) - axis current response accomplished by backstepping design techniques.
6. Conclusion and Remarks

In this study, modeling and synthesis of a sensorless control algorithm-based adaptive scheme for a class of nonlinear systems were achieved. Some new results in terms of designing an estimator have been presented successfully, and the researchers proposed an acceptable limit of sampling intervals and timing delays with adequate design parameters. These guarantee the exponential convergence of variable estimation, prediction and parameter estimations according to the proposed stability theorem.

The presentation of an inter-sampled predictor ameliorates the bounds of sampling intervals, and by choosing a timing delay two times the sampling period, the simulation results for PMG confirmed that the proposed adaptive estimator offers rapid transient response, which in turn makes the control task easier, and increases the validity of the estimator for unknown disturbances and uncertain armature resistance, offering smooth motion at low speed and efficient operation at high rotor speed.

The originality of this contribution lies in its consideration of the difficulties within such systems and recognition of control problem complexity, which are affected by the non-linearity of the system dynamics and the uncertainty regarding the armature resistance.

It should be emphasized that minimizing the number of appliances or using smart detectors will reflect positively on the reliability and dynamic behavior of electric systems, improving on-line monitoring of unmeasured quantities and thus improving security and saving cost.

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Appendix A: Simulink model and the corresponding practical connection of sensorless control technology based on an adaptive estimator scheme have been done recently.