Observer-Based Excitation Control for Transient Stabilization of the Single Machine Infinite Bus System

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***Abstract*— The availability of excitation controllers to enhance transient stability has regained significant relevance in recent years, due to the unprecedented ongoing changes in power systems. Yet, the practical deployment of many reported control schemes is hampered by the fact that their implementation requires the measurement of the full state vector. Our main contribution is to address this fundamental obstacle by proposing an observer-based excitation controller using modern phasor measurement technology. For this purpose, a linear time-varying observer scheme for the generator frequency and the internal voltage is derived. This observer is then combined with a classical passivity-based excitation controller. Stability of the resulting nonlinear observer-based closed-loop system is shown by deriving an ISS-based separation principle. The performance of the proposed approach is demonstrated via simulation example.**

I. INTRODUCTION

The recent changes in the energy generation mix have boosted the interest and relevance of rigorous stability analysis and control of electrical power systems [1]. These kind of analyses have always represented a challenge given the inherent non-linear structure of the power systems, the presence of uncertainties (both parametric and structural), perturbations and the impossibility of measuring all state variables [2], [3]. With respect to the last point, recently the development of *dynamical state estimators* has become increasingly relevant, not only for monitoring, but also for control purposes [4], [5].

One of the most prominent control tasks in power systems is to improve transient stability, e.g. by enlarging the critical clearing time after a fault. The main controllers of interest in this setting are excitation controllers. Due to the increasing penetration of volatile renewable energy sources and power-converter-interfaced devices threatening system stability, the problem of excitation control design has become increasingly important in recent years [2], [6], [7]. Traditionally, excitation control design has used the rotor speed and position, voltage on generator terminals, and electric power as measurement variables, and P(I)-based automatic voltage regulators (AVRs) together with power system stabilizers (PSSs) have been employed for this purpose [2], [8], [9]. Yet, it has been shown that more advanced nonlinear control schemes have the potential to significantly enhance transient stability [6], [7]. As demonstrated in [10], this applies in particular to passivity-based control schemes following the interconnection and damping assignment passivity-based control (IDA-PBC) methodology introduced in [11].

A common property of such advanced excitation control schemes is that they are (nonlinear) state feedback controllers. For a long time this fact has hampered their practical implementation, since most often the full state vector of the synchronous machine is not measurable [4], [5]. Yet, the increasing deployment of phasor measurement units (PMUs) opens new possibilities for observer-based control designs [2], [12]–[14].

In that regard, the main contribution of the present paper is an observer-based implementation of the IDA-PBC originally developed in [10]. For our derivations, we consider the well-known single-machine-infinite-bus (SMIB) scenario with the standard flux-decay model [2], [8]. The SMIB scenario has been extensively studied both in the power and the control systems literature since it captures many important phenomena in power systems operation [2], [8], [10], [15]. Our approach is characterized by the following two features:

1) We derive a linear time-varying observer capable of estimating the frequency and the quadrature axis internal voltage of the generator. Compared to the related result [16], our proposed observer is uniformly globally convergent and also serves to estimate the frequency, in addition to the internal generator voltage. For its implementation, we use the measured load angle, active power and terminal current of the generation unit, which all are measurements that can be provided using modern PMU technologies [2], [12].

2) The closed-loop system resulting from combining IDA-PBC control reported in [10] and our proposed observer is nonlinear. Hence, establishing stability of the observer-based closed-loop system is nontrivial. We tackle this challenge in a two-step procedure. At first, we show that the controlled SMIB system is input to state stable (ISS) with respect to the estimation error. Inspired by [17], this ISS property is then used to derive

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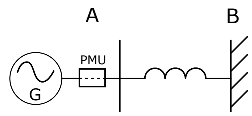

Fig. 1. Single machine infinity bus diagram.

a separation principle, *i.e.,* the controller and the observer can be designed independently. We remark that the latter is a rather unusual property in the case of non-linear systems.

The remainder of the paper is organized as follows: In Section II the physical description and mathematical model of the SMIB system is presented; in Section III the observer design methodology is introduced; later, in Section IV, some ISS properties are established; in Section V, the stability properties of the observer–based control for the SMIB are given; finally, in the last section, a numeric evaluation is presented.

II. SMIB DESCRIPTION

The SMIB system consists of a single generator connected to an infinite bus through an inductive line, as shown in the diagram in Figure 1. In this paper, the well-known third order (flux decay) model is considered [9], [10], [8, Chap. 4], which is described by

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= \frac{\omega_o}{2H}(P - P_e - Dx_2), \\ \dot{x}_3 &= \frac{1}{T'_{d0}}(u + E - x_3 + (X_d - X'_d)I_d), \end{aligned} \tag{1}$$

where $x_1 \in \mathbb{R}$ stands for the load angle, $x_2 \in \mathbb{R}$ is the rotor speed deviation from the synchronous speed and $x_3 \in \mathbb{R}$ is the quadrature axis internal voltage. The control input $u \in \mathbb{R}$ is the field excitation signal with $E \in \mathbb{R}$ being a constant offset. The (constant) mechanical power delivered to the generation unit is represented by $P \in \mathbb{R}$, while P_e denotes the electric power delivered by the generator. Finally, I_d corresponds to the d-axis current. The positive constants are the generator inertia time constant H, the damping factor D, the direct-axis transient open circuit time constant T'_{d0}, the direct-axis reactance X_d and the direct-axis transient reactance X'_d. Furthermore, the electric power P_e in (1) and the d-axis current I_d are given by

$$P_e = \frac{E_B}{X'_d + X_\ell} x_3 \sin(x_1), \tag{2}$$

$$I_d = \frac{1}{X'_d + X_\ell}\left(x_3 - E_B \cos(x_1)\right), \tag{3}$$

where $E_B \in \mathbb{R}$ is the voltage magnitude at the infinite bus and $X_\ell \in \mathbb{R}$ the line impedance.

TABLE I

DEFINITION OF THE GENERATOR PARAMETERS IN (4)

Parameter	Definition
b_1	$\frac{\omega_0 E_B}{2H(X'_d+X_\ell)}$
b_2	$\frac{\omega_0 D}{2H}$
b_3	$\frac{(X_d - X'_q)E_B}{T'_{d0}(X'_d+X_\ell)}$
b_4	$\frac{X_d - X'_d}{T'_{d0}(X'_d+X_\ell)}$

After the substitution of (2) and (3) in (1), the SMIB system is rewritten in compact form as

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= -b_1 x_3 \sin(x_1) - b_2 x_2 + P, \\ \dot{x}_3 &= b_3 \cos(x_1) - b_4 x_3 + E + u, \end{aligned} \tag{4}$$

where the short-hands b_i with $i = \{1, 2, 3, 4\}$ are defined in Table I.

For the observer-based excitation control design, we make the following assumption:

Assumption 1. *The quantities x_1, P_e and I_d in* (1)*,* (2) *and* (3)*, respectively, are measurable.*

Following [12], the previous assumption is reasonable considering the introduction of fast PMUs aimed to control, which are installed at the generator rotor and allow the angle measurement together with the voltage and power.

At this point it is important to recognize the following property, reported in [10], which is fundamental to formulate the transient stabilization problem for power systems.

Property 1. Consider $x = [x_1, x_2, x_3]^T \in \mathbb{R}^3$. When the operation of the system (4) is restricted to the closed set

$$\mathcal{D}_\delta = \left\{ x \ \in \mathbb{R}^3 \mid 0 \le x_1 \le \frac{\pi}{2} - \delta_1;\ \delta_1 \le x_3 \right\},$$

there exists in $\mathcal{D}_\delta$ a locally stable equilibrium point $x_\star = [x_{1\star}, 0, x_{3\star}]^T$, which is the solution of

$$\begin{aligned} -b_1 x_{3\star} \sin(x_{1\star}) + P &= 0, \\ b_3 \cos(x_{1\star}) - b_4 x_{3\star} + E &= 0, \end{aligned}$$

whenever

$$E > \frac{b_4 P}{b_1} - b_3.$$

Remark 1. The transient stabilization problem for the SMIB system is formulated with respect to the equilibrium point $x_\star$ in the sense that its region of attraction must be as large as possible.

III. LINEAR TIME-VARYING OBSERVER DESIGN

In this section the proposed observer for the SMIB system is presented. Its design takes advantage of measurements provided by the PMU as described in Assumption 1. Hence, the representation presented in (1) is used to carry the design out.

The main advantage of considering the existence of measuring instruments comes from the fact that the representation (1) can be viewed as a linear system subject to some external measurable variables. Hence, it is possible to consider a classical Luenberger observer. However, some conditions must be taken into consideration in order to propose its structure. From the mechanical variables, only x_1 is available for measurement according to Assumption 1. Thus, a natural choice for the corrective terms of the mechanical sub–system is to make them to depend on x_1. Under this condition, the first two equations of the estimation scheme are given by

$$\begin{aligned}\dot{\hat{x}}_1 &= \hat{x}_2 - L_1(\hat{x}_1 - x_1),\\ \dot{\hat{x}}_2 &= \frac{\omega_o}{2H}(P_m - P_e - D\hat{x}_2) - L_2(\hat{x}_1 - x_1),\end{aligned} \tag{5}$$

with $L_1 \in \mathbb{R}$, $L_2 \in \mathbb{R}$ the mechanical gains.

Due to the impossibility of measuring the electrical state x_3, but considering that P_e, I_d and I_q are measurable through the PMU, the third corrective term depends on the estimated active power

$$\hat{P}_e = \frac{E_B}{X'_d + X_\ell}\sin(x_1)\hat{x}_3.$$

Therefore, the third equation of the observer takes the form

$$\dot{\hat{x}}_3 = \frac{1}{T'_{d0}}\left(u + E - \hat{x}_3 + (X_d - X'_d)I_d\right) - L_3(\hat{P}_e - P_e), \tag{6}$$

with $L_3 \in \mathbb{R}$ the electrical gain.

The convergence properties of the proposed observer are proved in the next proposition.

Proposition 1. *Consider the SMIB system represented in the form* (1) *with Assumption 1. Furthermore, assume that all the system parameters are positive and known. Under these conditions, the observer* (5) – (6) *with* L_1, L_2 *and* L_3 *such that for all* $t \geq t_0$

$$L_1 > 0,\ L_2 > 0,\ \frac{1}{T'_{d0}} + L_3\frac{E_B\sin(x_1)}{X'_d + X_\ell} > 0, \tag{7}$$

guarantees that

$$\lim_{t\to\infty}\left\{\begin{bmatrix}\hat{x}_2\\ \hat{x}_3\end{bmatrix} - \begin{bmatrix}x_2\\ x_3\end{bmatrix}\right\} = 0,$$

uniformly in the initial time.

Proof. Define the observation error $\varepsilon = \hat{x} - x$. Considering the system (1) and the observer (5) – (6), the dynamic behavior of ε is described by

$$\dot{\varepsilon} = A_o(t)\varepsilon, \tag{8}$$

with

$$A_o(t) = \begin{bmatrix} -L_1 & 1 & 0\\ -L_2 & -\frac{\omega_0 D}{2H} & 0\\ 0 & 0 & -\left(\frac{1}{T'_{d0}} + \frac{L_3 E_B\sin(x_1)}{X'_d + X_\ell}\right)\end{bmatrix}.$$

$A_o(t)$ results continuous and bounded considering that $\sin(x_1)$ also possess these properties.

Consider now a symmetric positive definitive matrix $P = \operatorname{diag}\{p_1, p_1/L_2, p_3\}$. Choosing the gains L_i, $i = \{1,\,2,\,3\}$, according to (7), we obtain

$$Q(t) = PA_o(t) + A_o^T(t)P, \tag{9}$$

given by

$$Q(t) = \begin{bmatrix} -2p_1L_1 & 0 & 0\\ 0 & -p_1\frac{\omega_0 D}{L_2 H} & 0\\ 0 & 0 & -2p_3\left(\frac{1}{T'_{d0}} + \frac{L_3 E_B\sin(x_1)}{X'_d + X_\ell}\right)\end{bmatrix},$$

which is a continuous, bounded and symmetric negative definite matrix.

The proof is completed by invoking well–known results from the stability theory of linear time–varying systems to show that the equilibrium point $\varepsilon = 0$ is uniformly exponentially stable [18]. □

Remark 2. It is worth noting that the structure and stability properties of the proposed observer constitute a paramount example of the advantage of exploiting modern (PMU) measuring devices, to design observation schemes with simple structure and provable stability properties.

Remark 3. Assuming the knowledge of the parameters, as is done in Proposition 1, imposes a constraint for the proposed design. However, it is the authors belief that this condition can be removed using well–known theory of adaptive linear observers. Current research is carried out in this sense.

Remark 4. Both, the simple structure of the observer and the simple arguments used to prove its convergence properties, will be fundamental to state the stability properties of the whole observer–based closed–loop system considered in this paper.

IV. PASSIVITY–BASED CONTROL OF THE SMIB SYSTEM

This section is devoted to the presentation of some identified ISS properties of the IDA-PBC for the SMIB system presented in [10]. To this end, it is first necessary to formulate the following property of the full–state feedback version of the aforementioned control scheme.

Property 2. The SMIB system (4) in closed–loop with the control law

$$u = -k_v b_1(\cos(x_{1\star}) - \cos(x_1)) - \alpha_1\alpha_2\left(\frac{b_3}{b_1} + k_v\right)\tilde{x}_1 - \alpha_1 x_2 - \left(\frac{b_3}{b_1}\alpha_2 - b_4 + k_v\alpha_2\right)\tilde{x}_3, \tag{10}$$

where $\tilde{x}_i = x_i - x_{i\star}$ for $i = \{1, 2, 3\}$, and tuning parameters $k_v \geq 0$ and

$$\alpha_2 \geq \frac{b_1 b_4}{b_3}, \qquad \alpha_1 < -\frac{b_1}{\alpha_2},$$

leads to a Port-Controlled Hamiltonian (PCH) structure given by

$$\dot{x} = [\mathbf{J}_d - \mathbf{R}_d]\frac{\partial H_d(x)}{\partial x}, \tag{11}$$

with

$$\mathbf{J}_d = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & \alpha_1 \\ 0 & -\alpha_1 & 0 \end{bmatrix}, \; \mathbf{R}_d = \begin{bmatrix} 0 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & \frac{b_3}{b_1} + k_v \end{bmatrix},$$

while $H_d(x) = H(x) + H_a(x)$, where

$$H(x) = \frac{1}{2}x_2^2 + b_1 x_3\big(\cos(x_{1\star}) - \cos(x_1)\big) - P\tilde{x}_1 + \frac{b_1 b_4}{2b_3}\tilde{x}_3^2,$$

and

$$H_a(x) = \frac{1}{2}\left(\alpha_2 - \frac{b_1 b_4}{b_3}\right)(\alpha_1\tilde{x}_1 + \tilde{x}_3)^2 + b_1\alpha_1\Bigg[\tilde{x}_1\cos(x_{1\star}) - \sin(x_1) + \frac{b_4\alpha_1}{2b_3}\left(\tilde{x}_1^2 + \frac{2}{\alpha_1}\tilde{x}_1\tilde{x}_3 + x_{1\star}^2\right)\Bigg].$$

The control (10) ensures that the equilibrium point $x_\star \in \mathcal{D}_\delta$ defined in Property 1 is asymptotically stable [10].

From the observer design perspective, the main feature of the control law (10) lies in the fact that it is linear with respect to the unmeasurable states x_2 and x_3, the observer-based version of the control law can be written in the very amenable way given by

$$u_o = u + \Phi^T\varepsilon, \tag{12}$$

where $\varepsilon = \hat{x} - x$, u is given by (10) and

$$\Phi = \left[\begin{array}{c} 0 \\ -\alpha_1 \\ -\left(\frac{b_3}{b_1}\alpha_2 - b_4 + k_v\alpha_2\right) \end{array}\right].$$

This structure together with the control law (12) gives as a result that the closed–loop system presented in (11) takes the form

$$\dot{x} = [\mathbf{J}_d - \mathbf{R}_d]\frac{\partial H_d(x)}{\partial x} + \Gamma\varepsilon, \tag{13}$$

with $\Gamma \in \mathbb{R}^{3\times 3}$ defined as

$$\Gamma = \left[\begin{array}{c} 0_{2\times 3} \\ \Phi^T \end{array}\right].$$

With (12) at hand, it is possible to formulate the following proposition.

Proposition 2. *Consider the SMIB system represented by* (4) *in closed–loop with the observer–based control law* (12)*. Assume the conditions imposed in Property 2 are satisfied. Under these conditions system* (13) *defines an ISS mapping from the input* ε *to the output* x*.*

Proof. Consider the positive definite function $H_d(x)$ introduced in Property 2 whose time derivative along the trajectories of (13) is given by

$$\dot{H}_d = -\frac{\partial H_d(x)}{\partial x}^T\mathbf{R}_d\frac{\partial H_d(x)}{\partial x} + \frac{\partial H_d(x)}{\partial x}^T\Gamma\varepsilon \tag{14}$$

if $\varepsilon \neq 0$ then (14) can be written as

$$\dot{H}_d = -\frac{\partial H_d(x)}{\partial x_{23}}^T\mathbf{R}_{d1}\frac{\partial H_d(x)}{\partial x_{23}} + \frac{\partial H_d(x)}{\partial x_3}\left(\Phi_1^T\varepsilon_{23}\right),$$

with $\varepsilon_{23} = [\varepsilon_2, \varepsilon_3]^T$ and

$$\frac{\partial H_d(x)}{\partial x_{23}} = \left[\begin{array}{c} \frac{\partial H_d(x)}{\partial x_2} \\ \frac{\partial H_d(x)}{\partial x_3} \end{array}\right],$$

$$\Phi_1 = \left[\begin{array}{c} -\alpha_1 \\ -\left(\frac{b_3}{b_1} + k_v\right)\alpha_2 + b_4 \end{array}\right],$$

where the matrix

$$\mathbf{R}_{d1} = \begin{bmatrix} b_2 & 0 \\ 0 & \frac{b_3}{b_1} + k_v \end{bmatrix}$$

is symmetric positive definite.

Taking into consideration the positiveness of $\mathbf{R}_{d1}$, it holds that

$$\dot{H}_d \leq -(1-\theta)\frac{\partial H_d(x)}{\partial x_{23}}^T\mathbf{R}_{d1}\frac{\partial H_d(x)}{\partial x_{23}},$$

with $0 < \theta < 1$ and for all

$$\|\varepsilon_{23}\| \geq \frac{\|\Phi_1\|}{\theta\lambda_{\min}\big(\mathbf{R}_{d1}\big)}\left\|\frac{\partial H_d(x)}{\partial x_{23}}\right\|.$$

Then by applying well–known arguments (see for example [18]) it is proved that the map

$$\Sigma : \; \varepsilon \to x$$

is input to state stable. □

Remark 5. The ISS property of the IDA-PBC has been previously identified in a different scenario (see [17]) and states a very attractive feature since it does not depend on the structure of the observer.

V. OBSERVER–BASED CLOSED–LOOP STABILITY ANALYSIS

The final part of the contribution is presented in this section. It refers to the establishment of the stability properties of the whole observer–based closed–loop system composed by the SMIB system, the control (12) and the proposed observer (5) – (6). As it will be noticed in the next proposition, due to the simple structure of the latter and the attractive ISS property of the IDA-PBC, this goal is achieved in a quite straightforward way.

Proposition 3. *Consider the SMIB system represented by* (4) *in closed–loop with the control law* (12) *and the linear observer* (5) – (6) *under the assumptions of Proposition 1 and Proposition 2. Under these conditions the equilibrium point* $(x, \varepsilon) = (x_\star, 0)$ *is asymptotically stable.*

Proof. Consider the positive definite function

$$V_T = H_d(x) + \gamma \varepsilon^T P \varepsilon; \quad \gamma > 0,$$

with $P = \operatorname{diag}\{p_1, p_2, p_3\}$, $p_i > 0$ for $i = 1, 2, 3$.

The time derivative of V_T along the trajectories of (13) and (8) is given by

$$\dot{V}_T = -\frac{\partial H_d(x)}{\partial x}^T \mathbf{R}_d \frac{\partial H_d(x)}{\partial x} + \frac{\partial H_d(x)}{\partial x}^T \Gamma \varepsilon - \gamma \varepsilon^T Q(t) \varepsilon, \quad (15)$$

where $Q(t)$ is presented in (9).

Defining the vector

$$z = \begin{bmatrix} \frac{\partial H_d(x)}{\partial x} \\ \varepsilon \end{bmatrix},$$

then (15) can be written as $\dot{V}_T = -z^T A_1 z$ with

$$A_1 = \begin{bmatrix} \mathbf{R}_d & -\frac{1}{2}\Gamma \\ -\frac{1}{2}\Gamma^T & \gamma Q(t) \end{bmatrix}.$$

The proof is concluded by noticing that the matrix A_1 results positive semidefinite when γ is chosen suficiently large and by invoking the zero state detectability properties established in [10]. □

VI. NUMERICAL EVALUATION

The numerical evaluation is divided into two steps: Assuming an open–loop operation, the convergence properties of the observer are evaluated; later on, the closed–loop performance is evaluated.

In particular, for the closed–loop evaluation, the main interest is focused on the transient stability properties of the system.

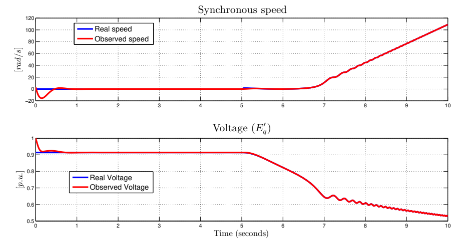

Fig. 2. State trajectories convergence under open–loop operation.

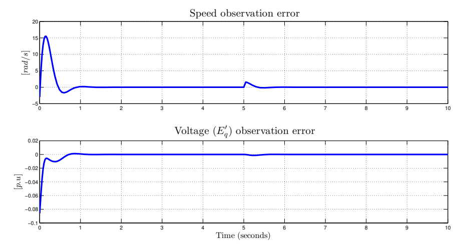

Fig. 3. Errors convergence under open–loop operation.

A. Open–loop convergence

The evaluation considers the following conditions: It is assumed that the initial operation of the SMIB system corresponds to the equilibrium point $x_\star$ while a different value for the observer initial conditions are considered. Once it is verified that the estimated trajectories converge to the actual behavior of the system, a short circuit disturbance is introduced whose magnitude is such that the open–loop system is not able to reject. After this event, as expected, the state trajectories of the system tend to infinity and it is verified that, even under this stringent situation, the behavior of the observer follows the behavior of the system.

The parameters and initial conditions for the SMIB system, taken from [9], are included in Table II while the observer gains were set to

$$L_1 = 10, \qquad L_2 = 20, \qquad L_3 = 10\sin(x_1).$$

This set of gains satisfies the conditions given in (7), Proposition 1.

In Figure 2 the behavior of the state trajectories are shown. It can be verified that the convergence is achieved in both situations, under stable and unstable operation. In order to evaluate in a better way the convergence speed, in Figure 3 the error between these trajectories is shown.

B. Closed–loop performance

Once the convergence properties in open-loop operation have been verified, in this section the attention is given to the closed–loop performance of the system.

In order to carry this evaluation out, the implemented experiment assumed that the SMIB-control system initially operates in $x_\star$ while the information provided by

TABLE II

PARAMETERS OF THE GENERATOR

Parameters	Value
Inertia time constant (H)	6 [s]
Nominal frequency (ω_o)	120π $[rad/s]$
Synchronous reactance (X_d)	1.2 [p.u.]
Transitory reactance (X_d')	0.3 [p.u.]
Transitory time (T_{d0}')	5 [s]
Mechanical power (P_m)	32.31 [p.u.]
Damping factor (D)	0 [p.u]
Infinite bus voltage (E_B)	1 [p.u.]
Line reactance (X_ℓ)	0.5 [p.u.]

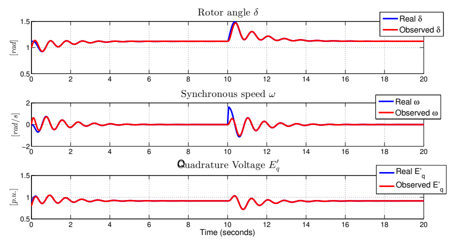

Fig. 4. State trajectories convergence in closed–loop operation.

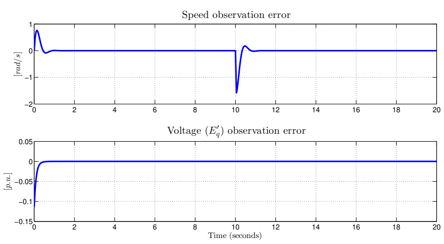

Fig. 5. Errors convergence in closed–loop operation.

the observer corresponds to different initial conditions. This situation is maintained until the observer states converge to the actual trajectories. At this time, a short circuit disturbance is introduced. As predicted by the theory, Figure 4 shows that the control law makes possible to recover a stable operation after the disturbance vanishes while in Figure 5 the error trajectories are included.

VII. CONCLUDING REMARKS

In this paper a solution to the transient stabilization problem of the SMIB system has been provided by proposing an observed–based control strategy. The main feature of the contribution lies in the simple structure of the observer scheme obtained by considering at a fundamental level of the design the possibility of using modern measuring devices, *i.e.*, the PMUs. The final result was an observer–based closed–loop system for which a formal stability analysis was established. This analysis also provides a separation principle between the controller and the proposed observer, *i.e.*, the controller and the observer can be designed independently, a property that is unusual to have in the case of non–linear systems. From a prospective point of view, the value of the contribution lies in the fact that the approach followed in this paper seems to be viable to consider more elaborated systems like multi–machine networks. This topic is under current research.

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