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Nonlinear Adaptive Control of Networked Power Generators with Remote Measurement Units

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***Abstract*—A nonlinear adaptive control law for the stabilization of synchronous generators in a power network is designed, based on the new possibilities related with Smart Grids, in particular the insertion of remote measurements provided by Phasor Measurement Units (PMU). The proposed control system is designed in a robust way in order to cope with several uncertainties like the network parameters, and the intrinsic time delay on remote measurements. The proposed controller stability is rigorously proved, and computer simulations illustrate its good behavior, and suggest that the new measurement and data transmission devices can bring even better performance.**

I. Introduction

Recently Smart Grids have become a very important trend in several research communities. Their new technological possibilities open the path to solve several hard problems in the literature. This paper aims exactly in investigating a new possibility on the control of networked power plants (power generators) using the rather new devices of Smart Grids known as Phasor Measurement Units (PMU). These devices are far beyond SCADA, and let one envisage the use of real time remote measurements on control schemes.

In the last three decades, the power systems have been growing in complexity and extension. The systems that were, at first, small and near the delivery point have spread to become interconnected, larger and more complex systems. One can see, for example, the evolution of the European system in [12]. This increase in complexity is important and necessary, and allows us to use the system at its full capability, but also makes the system more susceptible to disturbances and new phenomena, like inter-area oscillations ([12]). In order to monitor these systems and acquire data to further studies, the measurement devices called Phasor Measurement Units are being widely developed and tested.

From the point of view of Control Engineering, the power systems urge for more modern and accurate techniques. Due to the new reality of power systems, the classic controllers: Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS) still largely used, are now decreasing in performance because the growing stress on the power systems' operation. The objective of the control of synchronous generator in a power system is to ensure Stability and Voltage Regulation even during network changes, failure and transient dynamics of others generators connected in the network. This task is even more complex due to non-linearity, parameter uncertainty and disturbances in the systems [11].

In [7] and [4] nonlinear adaptive laws are proposed, which achieve transient stabilization and voltage regulation, but the models neglect the perturbations from the transient state of others generators. Good results were obtained by studying a generator g_r in a network of N generators ([5], [14]) and using the infinite bus model of a power network. In this context the adaptive law developed in [14], despite its complexity, guarantees transient stabilization and $\mathcal{L}_2$ and $\mathcal{L}_\infty$ disturbance attenuation using only local data and under reasonable assumptions. Several other works in the literature have addressed this field in the last decades ([3], [9]) using different techniques, but without explicitly considering Smart Grids technologies.

In this work's main result, we studied the consequences of adding the measured data from PMUs in nonlinear adaptive laws developed following similar procedures than that in [14]. Even if the development and stability analysis are carried out in rigorous mathematical ways, controller robustness towards network parameters and data time delays are only illustrated by simulations. This procedure is a first step to verify the effectiveness of using these PMU for control, and to envisage future control schemes that will formally consider and deal with these disturbances, in particular the time delays.

First it was considered the insertion of undelayed measured data in the controller developed in [14] to check the performance gain remote measurements could provide compared to adaptations. It was then introduce continuing increasing delays to verify the robustness of the controller in respect to these time delays. Secondly, we propose a new nonlinear adaptive law considering the remote measurements. This control law performance is then illustrated in the simulation section face to real situations: short-circuit in a transmission line, inter-area oscillation and large parameter changes in the network. We end up the work by some conclusions and future work that can be developed from the present results.

II. Dynamic Model

The dynamic model of a power systems of N generators connected in a network is described by a $3N$-order nonlinear model:

$$\begin{aligned}\dot{\delta}_i &= \omega_i \\ \dot{\omega}_i &= -\frac{D_i}{2H_i}\omega_i + \frac{\omega_0}{2H_i}P_{mi} - \frac{\omega_0}{2H_i}P_{ei} \\ \dot{E}'_{qi} &= \frac{k_{ci}}{T'_{d0i}}u_{fi} - \frac{E'_{qi}}{T'_{d0i}} - \frac{(x_{di}-x'_{di})}{T'_{d0i}}I_{di}\end{aligned} \tag{1}$$

and, for the i-th generator, we have the following electrical equations:

$$\begin{aligned}P_{ei} &= E'_{qi}\sum_{j=1}^{n}\Big[E'_{qj}G_{ij}\cos(\delta_{ij}) + E'_{qj}B_{ij}\sin(\delta_{ij})\Big] \\ &= E'_{qi}I_{qi} \\ Q_{ei} &= E'_{qi}\sum_{j=1}^{n}\Big[E'_{qj}G_{ij}\sin(\delta_{ij}) - E'_{qj}B_{ij}\cos(\delta_{ij})\Big] \\ &\quad -x'_{di}\Big(I_{di}^2 + I_{qi}^2\Big) \\ &= E'_{qi}I_{di} - x'_{di}\Big(I_{di}^2 + I_{qi}^2\Big) \\ I_{di} &= \sum_{j=1}^{n}\Big[E'_{qj}G_{ij}\sin(\delta_{ij}) - E'_{qj}B_{ij}\cos(\delta_{ij})\Big] \\ I_{qi} &= \sum_{j=1}^{n}\Big[E'_{qj}G_{ij}\cos(\delta_{ij}) + E'_{qj}B_{ij}\sin(\delta_{ij})\Big] \\ \delta_{ij} &= \delta_i - \delta_j \\ V_{ti} &= \sqrt{(x'_{di}I_{qi})^2 + (E'_{qi} - x'_{di}I_{di})^2}\end{aligned} \tag{2}$$

Where the first two equations of model 1 are the mechanical dynamic of the i-th generator involving the power angle δ_i(rad), the relative angular speed ω_i(rad/s), the active electrical power P_{ei}(p.u.), the input mechanical power P_{mi}(p.u.)(seen in this work as a unknown input), the synchronous angular speed ω_0(rad/s), the damping coefficient D_i(p.u.)(often neglected) and the inertia constant H_i(s). The others equations describe the electrical behaviour of the system, including disturbance, characteristics of the network and interactions between generators. In these equations are included the transient quadrature EMF E'_{qi}(p.u.), the control input u_{fi}(p.u.) to the thyristor amplifier, the gain k_{ci} of the excitation amplifier, the direct axis transient open circuit time constant T'_{d0i}(s), the direct axis reactance and the direct axis transient reactance x_{di}(p.u.) and x'_{di}(p.u.), respectively, the reactive electrical power Q_{ei}(p.u.), the direct and quadrature axis current I_{di} and I_{qi}, the terminal voltage V_{ti} and the G_{ij}(p.u.) and B_{ij}(p.u.) which are the elements of the i-th row and j-th column of the conductance matrix G and the susceptance matrix B. These two matrix represent the transmission network connecting the generators, they are changing as the load of any generator changes and are unmeasurable parameters.

I_{di} and I_{qi} play an important role in this model, as one can see they are the interactions between generators. Within these equations there are some states of the remote generators, the power angle and the quadrature EMF, and parameters of the network, such as the susceptance and conductance. Furthermore these parameters are unmeasurable as they depend on the whole state of the power system which is constantly changing.

In normal operation, called pre-fault, the system has as equilibrium point:

$$\begin{aligned}\delta_i &= \delta_{i0} \\ \omega_i &= 0 \\ E'_{qi} &= E'_{qi0}\end{aligned}$$

which implies

$$P_{ei} = P_{mi}$$

for $1 < i < n$, that must guarantees that the output voltage V_{ti} of each generator is equal to its reference constant value V^*_{ti}, $1 < i < n$.

As one can see, P_{ei} appears linearly in the dynamics of the angular speed and is also an output to be controlled once it must be held equal to P_{mi}. Furthermore it is measurable (available for feedback) and using it would give to the system a triangular structure, making it easier to design a controller.

Considering constant G_{rj} and B_{rj}, for $1 < j < n$ and using equation 2 we can derive the dynamic of P_{er}, the power output of the r-th generator:

$$\begin{aligned}\dot{P}_{er} &= \dot{E}'_{qr}I_{qr} + \dot{I}'_{qr}E_{qr} = \dot{E}'_{qr}\Big[I_{qr} + E'_{qr}G_{rr}\Big] \\ &\quad + E'_{qr}\sum_{j=1,j\neq r}^{n}\Big[\dot{E}'_{qj}G_{rj}\cos(\delta_{rj}) + \dot{E}'_{qj}B_{rj}\sin(\delta_{rj})\Big] \\ &\quad - E'_{qr}\sum_{j=1,j\neq r}^{n}\Big[E'_{qj}G_{rj}\sin(\delta_{rj}) - E'_{qj}B_{rj}\cos(\delta_{rj})\Big]\Big[\omega_r - \omega_j\Big]\end{aligned} \tag{3}$$

This last equation can be rearranged and the dynamics of the system with this new state variable can be represented as:

$$\begin{aligned}\dot{\delta}_r &= \omega_r \\ \dot{\omega}_r &= -\frac{D_r}{2H_r}\omega_r + \frac{\omega_0}{2H_r}P_{mr} - \frac{\omega_0}{2H_r}P_{er} \\ \dot{P}_{er} &= -\frac{1}{T'_{d0r}}P_{er} - \frac{(x_{dr}-x'_{dr})}{T'_{d0r}}I_{dr}I_{qr} - \frac{G_{rr}(x_{dr}-x'_{dr})}{T'_{d0r}}\frac{I_{dr}P_{er}}{I_{qr}} \\ &\quad - \frac{G_{rr}}{T'_{d0r}}\frac{P_{er}^2}{I_{qr}^2} + \Big[\frac{\frac{k_{cr}}{T'_{d0r}}I_{qr}^2 + \frac{G_{rr}k_{cr}}{T'_{d0r}}P_{er}}{I_{qr}}\Big]u_{fr} \\ &\quad - \Big(Q_{er} + B_{rr}\frac{P_{er}^2}{I_{qr}^2} + x'_{dr}(I_{dr}^2 + I_{qr}^2)\Big)\omega_r + \frac{P_{er}}{I_{qr}}R_r\end{aligned} \tag{4}$$

Where the term

$$\begin{aligned}R_r &= \sum_{j=1,j\neq r}^{n}\dot{\bar{E}}'_{qj}\Big[G_{rj}\cos(\delta_{rj}) + B_{rj}\sin(\delta_{rj})\Big] \\ &\quad + \sum_{j=1,j\neq r}^{n}\omega_j\Big[E'_{qj}G_{rj}\sin(\delta_{rj}) - E'_{qj}B_{rj}\cos(\delta_{rj})\Big]\end{aligned}$$

represents the remote network dynamics, it means, the disturbance on the r-th generator caused by the remote generators out of their equilibrium points (as one can see, $R_r = 0$ when in

equilibrium). This expression of the network interconnection can not be measured, mainly because of the presence of G_{rj}, B_{rj} and $\tilde{E}'_{qj} = E'_{qj} - E'_{qj0}$, $1 < j < n$, $j \neq r$. R_r represents the main parameter requiring telecommunication of remote data, and as a consequence, plays a crucial role in this work.

We then define a new parametrization: $\theta_{1r} = \frac{1}{T'_{d0r}}$, $\theta_{2r} = \frac{(x_{dr}-x'_{dr})}{T'_{d0r}}$, $\theta_{3r} = \frac{G_{rr}(x_{dr}-x'_{dr})}{T'_{d0r}}$, $\theta_{4r} = \frac{G_{rr}}{T'_{d0r}}$, $\theta_{5r} = \frac{k_{cr}}{T'_{d0r}}$, $\theta_{6r} = \frac{G_{rr}k_{cr}}{T'_{d0r}}$ as the generator electrical constant parameters.

In practice, the exact values of some parameters are hard to obtain, specially G_{rr}, B_{rr} and P_{mr}. This last one depends on the turbine mechanical dynamics and the load, which exact value is unknown. The first two parameters may change due to electrical failures and perturbations. In this work, we consider as known the parameters ω_0, H_r, D_r, T'_{dr0}, x_{dr}, x'_{dr} and k_{cr} which are mechanical or electrical parameters of the generator, and can be obtained by off-line experiments. In the same way, the unknown parameters are assumed to be within known positives bounds (G_{rrm}, G_{rrM}), (B_{rrm}, B_{rrM}), (P_{mrm}, P_{mrM}) with P_{mr} being a class $\mathcal{C}^1$ function and $|\dot{P}_{mr}(t)| \leq \dot{P}_{Mr}$.

Physical considerations about load, transmission network and mechanical turbines make the considerations above reasonable in practical applications.

III. Control Proposition

In this chapter we develop our main result, a nonlinear adaptation law for the control of the synchronous generator based on the model described above and the design techniques found in [10] and [13] and developed in [14].

First we define the power angle and the relative angular speed errors as:

$$\begin{aligned} \tilde{\delta}_r &= \delta_r - \delta_{rs} \\ \tilde{\omega}_r &= \omega_r - \omega_r^* \end{aligned}$$

Where δ_{rs} is the power angle constant reference value (the pre-fault value) and ω_r^*, the relative angular speed time-varying reference signal here defined as:

$$\omega_r^* = -\frac{5}{4}k_{\delta r}\tilde{\delta}_r \tag{5}$$

We define the active electrical power time-varying reference signal as:

$$\begin{aligned} P_{er}^* &= \frac{2H_r}{\omega_0}\left[\frac{5}{4}k_{\omega r}\tilde{\omega}_r + \frac{5}{4}k_{\delta r}\omega_r \right. \\ &\quad \left. -\frac{D_r}{2H_r}\omega_r^* + \tilde{\delta}_r + \frac{1}{k_{\omega pr}}\tilde{\omega}_r\right] + \hat{P}_{mr} \end{aligned} \tag{6}$$

Where $\hat{P}_{mr}$ is the estimate of the input mechanical power, obtained by the observer:

$$\begin{aligned} \hat{P}_{mr} &= \phi_r + \frac{2H_r}{\omega_0}\left(\frac{5}{4}k_{per} + \frac{k_r}{4} + \frac{1}{k_r} + \frac{\omega_0^2}{16H_r^2}k_{\omega pr}\right)\omega_r \\ \dot{\phi}_r &= \left(\frac{5}{4}k_{per} + \frac{k_r}{4} + \frac{1}{k_r} + \frac{\omega_0^2}{16H_r^2}k_{\omega pr}\right)\left[-\phi_r + \frac{D_r}{\omega_0}\omega_r \right. \\ &\quad \left. + P_{er} - \frac{2H_r}{\omega_0}\left(\frac{5}{4}k_{per} + \frac{k_r}{4} + \frac{1}{k_r} + \frac{\omega_0^2}{16H_r^2}k_{\omega pr}\right)\omega_r\right] \end{aligned} \tag{7}$$

Finally, we can define the active electrical power tracking error:

$$\tilde{P}_{er} = P_{er} - P_{er}^*$$

Now that the tracking error system is complete we may present the closed loop dynamic for the error system as:

$$\begin{aligned} \dot{\tilde{\delta}}_r &= -\frac{5}{4}k_{\delta r}\tilde{\delta}_r + \tilde{\omega}_r \\ \dot{\tilde{\omega}}_r &= -\left(\frac{5}{4}k_{\omega r} + \frac{D_r}{2H_r}\right)\tilde{\omega}_r - \tilde{\delta}_r + \frac{\omega_0}{2H_r}\tilde{P}_{mr} - \frac{\omega_0}{2H_r}\tilde{P}_{er} \\ &\quad -\frac{1}{k_{\omega pr}}\tilde{\omega}_r \\ \dot{\tilde{P}}_{er} &= -\frac{5}{4}k_{pe}\tilde{P}_{er} + \frac{\omega_0}{2H_r}\tilde{\omega}_r + \frac{P_{er}}{I_{qr}}R_r - \frac{\tilde{G}_{rr}}{T'_d}\frac{P_{er}^2}{I_{qr}^2} \\ &\quad -\tilde{G}_{rr}\frac{(x_{dr}-x'_{dr})}{T'_d}\frac{I_{dr}P_{er}}{I_{qr}} + \tilde{G}_{rr}\frac{P_{er}}{(I_{qr}^2 + \hat{G}_{rr}P_{er})}v'_r \\ &\quad -\tilde{B}_{rr}\frac{P_{er}^2}{I_{qr}^2}\omega_r + \pi_r - \left(\frac{5}{4}k_{\omega r} + \frac{5}{4}k_{\delta r} + \frac{5}{4}k_{per}\right. \\ &\quad \left. + \frac{k_r}{4} + \frac{1}{k_r} + \frac{\omega_0^2}{16H_r^2}k_{\omega pr} + \frac{1}{k_{\omega pr}}\right)\tilde{P}_{mr} \end{aligned} \tag{8}$$

Where v'_r is equal to:

$$v'_r = \frac{(\theta_5 I_{qr}^2 + \hat{\theta}_6 P_{er})}{I_{qr}}u_{fr} \tag{9}$$

with $\hat{\theta}_6 = \hat{G}_{rr}\theta_5$ (θ_5 as defined in chapter 2). And also the robustifying term:

$$\begin{aligned} \pi_r &= -\frac{k_{Rr}}{4}\frac{P_{er}^2}{I_{qr}^2}\tilde{P}_{er} - \frac{k_r}{4}\tilde{P}_{er}\left[P_{er}^2 + I_{dr}^2 I_{qr}^2 + \frac{I_{dr}^2 P_{er}^2}{I_{qr}^2}\right. \\ &\quad \left. + \frac{P_{er}^4}{I_{qr}^4}\left(1 + \omega_r^2\right) + \omega_r^2\left(I_{dr}^2 + I_{qr}^2\right)^2\right] - \frac{k_r}{4}\left(\frac{5}{4}k_{\omega r}\right. \\ &\quad \left. + \frac{5}{4}k_{\delta r} + \frac{5}{4}k_{per} + \frac{k_r}{4} + \frac{1}{k_r} + \frac{\omega_0^2}{16H_r^2}k_{\omega pr}\right. \\ &\quad \left. + \frac{1}{k_{\omega pr}}\right)^2\tilde{P}_{er} - \frac{k_r}{4}\frac{P_{er}^2}{I_{qr}^2}\tilde{P}_{er}R_r^2 \end{aligned} \tag{10}$$

and

$$\tilde{P}_{mr} = P_{mr} - \hat{P}_{mr}$$

being the observer tracking error with the time derivative equals to:

$$\begin{aligned} \dot{\tilde{P}}_{mr} &= -\left(\frac{5}{4}k_{per} + \frac{k_r}{4} + \frac{1}{k_r} + \frac{\omega_0^2}{16H_r^2}k_{\omega pr}\right)\tilde{P}_{mr} \\ &\quad + \dot{P}_{mr}. \end{aligned} \tag{11}$$

and:

$$
\begin{aligned}
v'_r &= -\frac{5}{4}k_{pe}\tilde{P}_{er} + \frac{\omega_0}{2H_r}\tilde{\omega}_r + \frac{5D_r k_{\delta r}}{4\omega_0}\omega_r + \tilde{B}_{rr}\frac{P_{er}^2}{I_{qr}^2}\omega_r \\
&+\tilde{G}_{rr}\left[\frac{(x_{dr}-x'_{dr})}{T'_d}\frac{I_{dr}P_{er}}{I_{qr}} + \frac{1}{T'_d}\frac{P_{er}^2}{I_{qr}^2}\right] + \frac{P_e}{T'_d} \\
&+\frac{(x_{dr}-x'_{dr})}{T'_d}I_{qr}I_{dr} + Q_e\omega_r + x_{dr}\big(I_{qr}^2 + I_{dr}^2\big)\omega_r \\
&+\frac{5}{4}k_\delta\big(\hat{P}_{mr} - P_e\big) + \frac{2H}{\omega_0}\omega \\
&+\frac{2H}{\omega_0}\left[\frac{5}{4}k_{\omega r} + \frac{1}{k_{\omega pr}}\right]\left[\left(\frac{5}{4}k_{\omega r} + \frac{D_r}{2H_r}\right)\tilde{\omega}_r + \tilde{\delta}_r \right. \\
&\left. +\frac{\omega_0}{2H}\tilde{P}_{er} + \frac{1}{k_{\omega pr}}\tilde{\omega}_r\right] + \pi_r \qquad (12)
\end{aligned}
$$

As one may notice, the term of remote data R_r appears in equation 12 , more precisely, in the term π_r. We suppose that the data to perform the calculation of this term will be measured by the PMU. These units allow us to collect remote information of others generators, knowing that we have, associated with R_r, a delay due data telecommunication.

Finally, we can define the Lyapunov Function for the system and apply equations 8 and 12 to obtain the dynamic of the adaptations $\hat{G}_{rr}$ and $\hat{B}_{rr}$:

$$
\begin{aligned}
\mathcal{W}_r &= \frac{1}{2}\Big(\tilde{\delta}_r^2 + \tilde{\omega}_r^2 + \tilde{P}_{er}^2 + \tilde{P}_{mr}^2\Big) \\
&+\frac{1}{2}\beta_{Brr}\tilde{B}_{rr}^2 + \frac{1}{2}\beta_{Grr}\tilde{G}_{rr}^2
\end{aligned}
$$

Where its time derivative is equals to:

$$
\begin{aligned}
\dot{\mathcal{W}}_r &= -\frac{5}{4}k_{\delta r}\tilde{\delta}_r^2 - \Big(\frac{5}{4}k_{\omega r} + \frac{D_r}{2H_r}\Big)\tilde{\omega}_r^2 + \frac{\omega_0}{2H_r}\tilde{P}_{mr}\tilde{\omega}_r \\
&-\frac{1}{k_{\omega pr}}\tilde{\omega}_r^2 - \frac{5}{4}k_{pr}\tilde{P}_{er}^2 + \pi_r\tilde{P}_{er} + \frac{P_{er}}{I_{qr}}R_r\tilde{P}_{er} \\
&-\Big(\frac{5}{4}k_{\omega r} + \frac{5}{4}k_{\delta r} + \frac{5}{4}k_{per} + \frac{k_r}{4} + \frac{1}{k_r} + \frac{\omega_0^2}{16H_r^2}k_{\omega pr} \\
&+\frac{1}{k_{\omega pr}}\Big)\tilde{P}_{mr}\tilde{P}_{er} + \dot{P}_{mr}\tilde{P}_{mr} - \tilde{B}_{rr}\left[\frac{P_{er}^2\omega_r\tilde{P}_{er}}{I_{qr}^2}\right. \\
&\left.+\beta_{Brr}\dot{\hat{B}}_{rr}\right] - \Big(\frac{5}{4}k_{per} + \frac{k_r}{4} + \frac{1}{k_r} + \frac{\omega_0^2}{16H_r^2}k_{\omega pr}\Big)\tilde{P}_{mr}^2 \\
&-\tilde{G}_{rr}\left[\frac{(x_{dr}-x'_{dr})}{T'_d}\frac{I_{dr}P_{er}}{I_{qr}}\tilde{P}_{er} + \frac{P_{er}^2\tilde{P}_{er}}{T'_dI_{qr}^2}\right. \\
&\left.-\frac{P_{er}v'_r\tilde{P}_{er}}{I_q^2 + \hat{G}_{rr}P_{er}} + \beta_{Grr}\dot{\hat{G}}_{rr}\right] \qquad (13)
\end{aligned}
$$

So, using the projection algorithm as defined in [14], the dynamics for the two adaptations are

$$
\begin{aligned}
\dot{\hat{G}}_{rr} &= Proj\left\{\frac{\tilde{P}_{er}}{\beta_{Grr}}\left[-\frac{(x_{dr}-x'_{dr})}{T'_d}\frac{I_{dr}P_{er}}{I_{qr}} - \frac{P_{er}^2}{T'_dI_{qr}^2}\right.\right. \\
&\left.\left.+\frac{P_{er}v'_r}{I_q^2 + \hat{G}_{rr}P_{er}}\right]\right\} \\
\dot{\hat{B}}_{rr} &= Proj\left(-\frac{\tilde{P}_{er}}{\beta_{Brr}}\frac{P_{er}^2}{I_{qr}^2}\omega_r\right) \qquad (14)
\end{aligned}
$$

Back to equation 13, by completing the squares and using the proprieties of $Proj(x)$, we can show that:

$$
\begin{aligned}
\dot{\mathcal{W}}_r &\leq -\frac{5}{4}\Big(k_{\delta r}\tilde{\delta}_r^2 + k_{\omega r}\tilde{\omega}_r^2 + k_{pr}\tilde{P}_{er}^2 + k_{per}\tilde{P}_{mr}^2\Big) \\
&+\frac{R_r(t)^2}{k_{Rr}} \qquad (15)
\end{aligned}
$$

which assure that all states are arbitrarily ultimately bounded, with the error region given by the disturbance $R_r(t)$ attenuated by the arbitrary design parameter k_{Rr}. Furthermore, if no transmission errors or delay corrupt the measurements, and if we could exactly obtain the measurement of the interconnection expression $R_r(t)$, then we could obtain a globally exponentially stable system by erasing the last term in (15). In the real case where errors and delays are intrisical to the system, the equations above shows that the system will be ultimately bounded.

IV. Simulations

To perform the simulation, the control developed here was applied at each generator of the well known Western System Coordinating Council (WSCC), a 3-machine, 9-bus system with parameters available in [2] and described as a two axis model:

$$
\begin{aligned}
\dot{\delta}_i &= \omega_i \\
\dot{\omega}_i &= -\frac{D_i}{2H_i}\omega_i + \frac{\omega_0}{2H_i}P_{mi} - \frac{\omega_0}{2H_i}P_{ei} \\
\dot{E}'_{di} &= -\frac{E'_{di}}{T'_{q0i}} - \frac{(x_{qi}-x'_{di})}{T'_{q0i}}I_{qi} \qquad (16) \\
\dot{E}'_{qi} &= \frac{k_{ci}}{T'_{d0i}}u_{fi} - \frac{E'_{qi}}{T'_{d0i}} - \frac{(x_{di}-x'_{di})}{T'_{d0i}}I_{di}
\end{aligned}
$$

where we considered in the simulations, that $D_i = 0$, for $1 \leq i \geq 3$. One may notice that this system is equivalent to the one described in chapter 2 by making $x_{qi} = x'_{di}$ neglecting, thus, the dynamic of the fast damper-winding E'_{di}.

The simulations were carried out to illustrate the performance of the controller during normal events, such as inter-area oscillation and some intense events as a short-circuit in a transmission line. For this last one we compare the results with the controller in [14] with the same parameters described in the article.

The inter-zone oscillation phenomenon was simulated by including, in the input mechanical power of one generator, a sinusoidal component with amplitude equals to 10% of the total input in low frequency, $1Hz$. A rather soft, but constant phenomenon while the short-circuit is a fast and

intense changing in the network and will show the controller robustness.

A. Transmission Line Short-Circuit

Here we present the effect of a three phase short circuit occurring at $t = 1s$. This is one of the hardest faults that can affect the system, but at the same time, a current fault that happens every day in average for a country wide system.

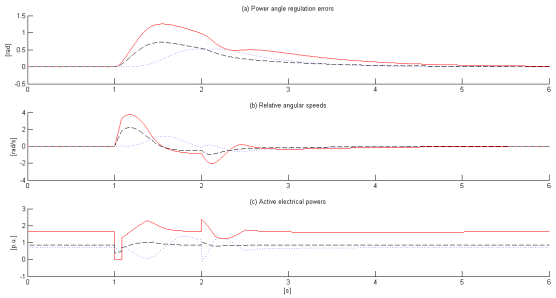

Fig. 1. Proposed controller [G1 (dot), G2 (solid), G3 (dash)]: a) $\delta_i - \delta_{is}$; b) ω_i; c) P_{ei}.

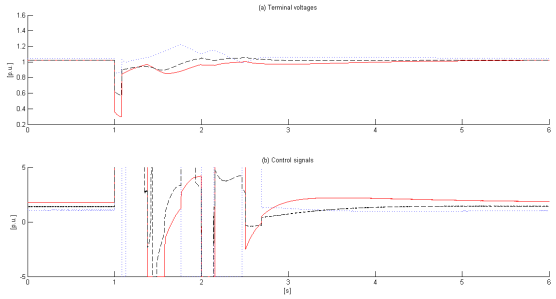

Fig. 2. Proposed controller [G1 (dot), G2 (solid), G3 (dash)]: a) V_{ti}; b) u_{fi}.

It can be seen in Fig 1, that the proposed controller allow all states of the three generators to be kept in reasonable bounds, and that they recover their original values from before the fault. In the same way the output voltage and the control input is shown in Fig 2.

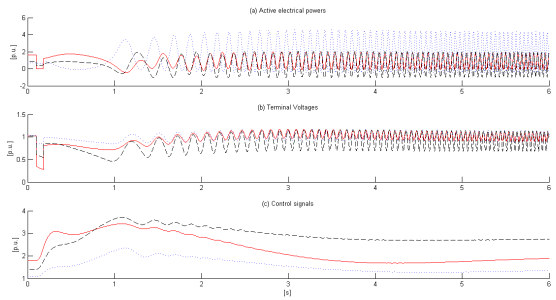

Fig. 3. Regulation with PSS [G1 (dot), G2 (solid), G3 (dash)]: a) P_{ei} ; b) V_{ti}; c) u_{fi}.

For comparison, the same fault is dealt with a PSS (Power System Stabilizer) controller. As we can see in Fig 3, the controller cannot hold such fault.

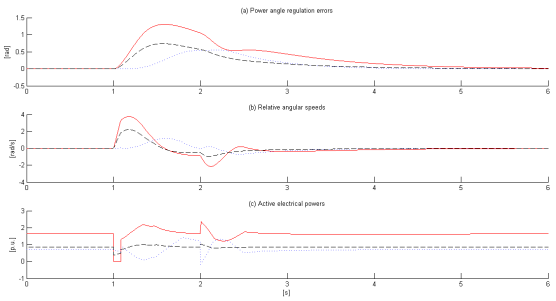

Fig. 4. Controller from [14] [G1 (dot), G2 (solid), G3 (dash)]: a) $\delta_i - \delta_{is}$; b) ω_i; c) P_{ei}.

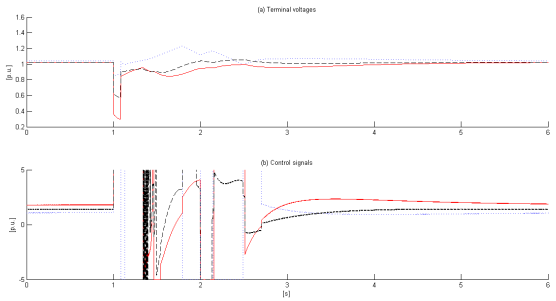

Fig. 5. Controller from [14] [G1 (dot), G2 (solid), G3 (dash)]: a) V_{ti}; b) u_{fi}.

Finally, the results for the controller proposed in [14] is presented in Fig 4 and Fig 5. In both groups of simulations, one can see that the proposed controller has very similar performances to [14], but with a simpler algorithm and with a smaller number of adaptations. Nevertheless both control algorithms managed to stabilize the system even in such critical situation, but the proposed algorithm is smoother which means less stress to the actuator.

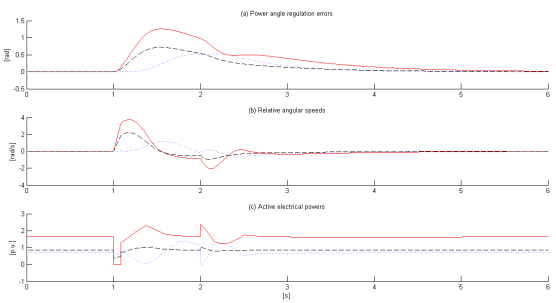

Fig. 6. Proposed controller [G1 (dot), G2 (solid), G3 (dash)]: a) $\delta_i - \delta_{is}$; b) ω_i; c) P_{ei}.

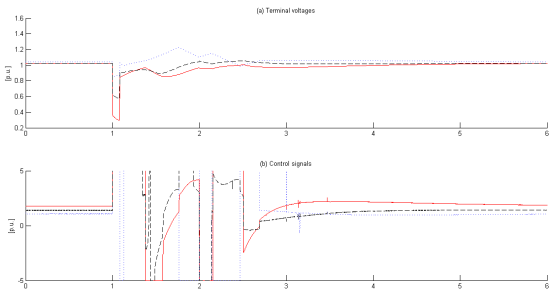

Fig. 7. Proposed controller [G1 (dot), G2 (solid), G3 (dash)]: a) V_{ti}; b) u_{fi}.

This last two figures (6 and 7) show the effects of adding a delay of $1s$ in $R_r(t)$. The delay represents the data transmission time from the PMU to the local central. For nowadays technologies $1s$ is quite a long delay, but shows that the effect of the data transmission is not relevant for the controller because the results were almost the same obtained by the controller without delay.

B. Inter-area Oscillations

In this section we will simulate the behaviour of the controller and the voltage output in the case of inter-zone oscillations.

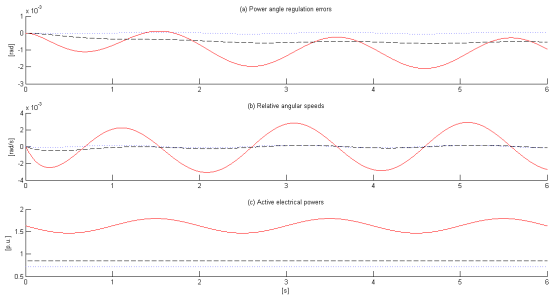

Fig. 8. Oscillation in G1 [G1 (dot), G2 (solid), G3 (dash)]: a) $\delta_i - \delta_{is}$; b) ω_i; c) P_{ei}.

In Fig 8, we show the response of the controller for an oscillation in the active electrical power in generator 2. As one can see, we have small error, which shows a the response of the controller to such event.

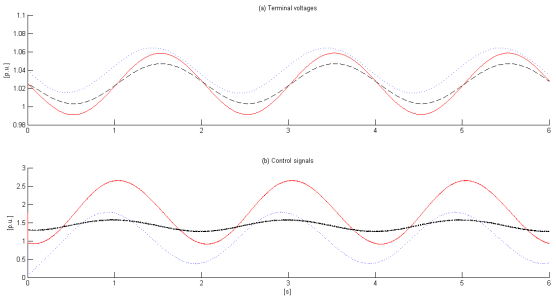

Fig. 9. Oscillation in G2 [G1 (dot), G2 (solid), G3 (dash)]: a)V_{ti}; b) u_{fi}.

In Fig 9 is the same scenario as Fig 8, but for the voltage output and the control signal. The control signal shows high amplitude oscillations in the same frequency of the mechanical power input. However, the output voltage remains stable in spite of the disturbance, with oscillations smaller than 5% of the current value.

V. Conclusion

The present work has developed a new control scheme inspired in previous works, in particular [14], but based in less adaptations and with a simpler design. ~~This new controller has also the advantage of being better fit for the use of remote measurements in its structure.~~

The good behaviour of the new controller can be appreciated in the proposed simulations, where the new controller was able to assure system's stability even face severe faults, and has shown to be as robust as the one in [14] even if much simpler.

In future works, we will continue to study how remote dynamics can be integrated to control schemes, and how time delays can be formally taken into account.

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