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Estimator-Based Adaptive Fuzzy Logic Control Technique for a Wind Turbine-Induction Generator System*

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Abstract

The control of a wind power plant, operating as an isolated power source, is analyzed. The plant consists of a wind turbine and a three-phase induction electric generator, connected by means of a gear box. The mathematical models of the wind turbine and of the electrical generator are indicated. The use of an Estimator-based Adaptive Fuzzy Logic control technique to govern the system is proposed. The results of a control test case are shown in order to demonstrate the reliability of the proposed control technique.

1 Introduction

Wind power plants are generally used to convert wind energy into electrical energy. These plants consist of a wind turbine and an electrical generator connected by means of a gear box. The wind turbine converts wind kinetic energy into mechanical energy and the latter into electrical energy by means of the electrical generator. These plants are controlled by an appropriate control system.

The flow field around a wind turbine is unsteady and three-dimensional. Mathematical models for such complex flows are available in the literature. They may be divided into momentum, vortex, and finite-difference models. The momentum models use actuator surfaces to approximate wind-turbine effects and subdivide the flow domain into a finite number of stream-tubes (Wilson and Lisseman, 1974; Strickland, 1975; Shankar, 1976; Templin, 1974; Lapin, 1975; Paraschivoiu, 1981; Loth and McCoy, 1983; Fortunato and De Martino, 1989). Vortex models simulate the wind-turbine blades and use bounded, distributed vortices (Brown, 1991; Wilson *et al.*, 1976; Holme, 1976; Wilson, 1978; Fanucci and Walters, 1976; Strickland *et al.*, 1979; Wilson and Walker, 1975, 1983; Wilson *et al.*, 1983). Finally, finite difference models solve the fluid-dynamic governing equations by means of finite-volume or finite-difference methods (Chviaropoulos and Papailiou, 1988; Rajagopalan and Fanucci, 1985; Fortunato *et al.*, 1995; Rajagopalan *et al.*, 1995).

To regulate these wind power plants, a control system must yield an asymptotic reduction of the disturbances in order to minimize the differences between the actual and reference values

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of the output voltage and frequency. Applications to wind-power plants of open-loop (Steinbuch, 1986) and closed-loop (Madsen, 1988; Sandhu and Dias, 1988) classical control techniques can be found in the literature.

In the present paper we propose the Estimator-based Adaptive Fuzzy Logic (EAFL) control, which represents an innovative type of adaptive fuzzy logic control system (Mendel, 1995; Andersen *et al.*, 1997). The EAFL controller continuously optimizes the internal parameters of the Fuzzy Logic Rule Base, in order to adapt these parameters to the system-dynamic behavior (Mendel, 1995; Andersen *et al.*, 1997). Indeed, starting from a first glance Fuzzy Logic Rule Base, the EAFL minimizes a cost function in order to adapt the fuzzy controller parameters to the controlled wind system. This control technique employs a gradient descent algorithm to minimize the cost function which is based on the control error estimated one step ahead. Such errors are estimated by using the Least Square Algorithm (LSA) in recursive form (Goodwin and Sin, 1984; Dambrosio, 1994; Dadone *et al.*, 1998).

The EAFL requires the observability of the controlled plant, while it does not require any a priori knowledge of its deterministic model. In the present paper, instead of a real wind plant, a numerically simulated wind system is considered. In particular, a rather simple momentum model for the wind turbine is adopted, while a complete dynamic model of the rotor and stator windings of the induction generator is employed (Fitzgerald *et al.*, 1992).

Taking into account that the power plant is assumed to be an isolated power source, the disturbances here considered are the wind speed variability and the external load changes. Obviously, the EAFL has to counterbalance such disturbance variables in order to control the system outputs represented by the voltage and by the rotational speed of the self-excited induction generator. The required control is obtained by acting on the control variables, which are assumed to be the resistance of the induction generator rotor windings (Fitzgerald *et al.*, 1992) and the transmission ratio of the gear box.

In the next sections, the mathematical models of the horizontal wind turbine and of the induction electrical generator are first outlined. Next, the Fuzzy Logic System and the Estimator-based Adaptive Fuzzy Logic control technique are described. Finally, some results of the application of the EAFL control algorithm to the numerically modelled wind system are presented.

2 Model of the Horizontal-Axis Wind Turbine

The mathematical model of a horizontal-axis wind turbine here employed is based on the stream-tube discretization (Wilson and Lisseman, 1974) . Momentum conservation in both the axial and tangential directions is considered. The aerodynamic characteristics of the wind turbine blades are represented by the lift (C_L) and drag (C_D) coefficients, which depend on the inflow angle. According to Wilson and Lisseman (1974), the thrust and torque acting on a blade element dr, at a distance r from the center of the rotor, are given by

$$\begin{aligned} dT &= \rho\,\pi\,r\,\sigma\,(1-a)^2\,V_0{}^2\,C_L\,\frac{\cos\phi}{\sin^2\phi}\left(1+\frac{C_D}{C_L}\tan\phi\right)dr, \\ dQ &= \rho\,\pi\,r^2\,\sigma\,(1+a')^2\,(\Omega\,r)^2\,C_L\,\frac{\sin\phi}{\cos^2\phi}\left(1-\frac{C_D}{C_L}\,\frac{1}{\tan\phi}\right)dr, \end{aligned} \tag{1}$$

where $\sigma = A_b/A$ is the solidity ratio, while A and A_b are the rotor area and the total blade area, respectively. Moreover, r, a, a', ϕ represent the air density, the axial and tangential induced velocity coefficients, and the inflow angle, respectively. Finally, Ω is the rotor angular speed, and V_0 is the undisturbed wind velocity. Following Eqs. (1), the wind turbine torque, Q_T, and power, P, are given by:

$$Q_T = \int_{R_{min}}^{R_{max}} dQ, \tag{2}$$

$$P = Q\,\Omega, \tag{3}$$

where R_{min}, and R_{max} represent the internal and external rotor radii, respectively. The wind-turbine power coefficient is evaluated from Eq. (3) as

$$C_P = \frac{P}{1/2\,\rho\,A\,{V_0}^3}\,. \tag{4}$$

In the present paper, we consider a three-blade horizontal-axis wind turbine. Its external, R_{max}, and internal, R_{min}, rotor radii are 5 m and 0.5 m, respectively. The considered standard conditions are the following: $V_0 = 10\,\mathrm{m/s}$; $P = 22\,\mathrm{kW}$; tip speed ratio $\Lambda = 7$, being $\Lambda = \Omega\,R_{max}/V_0$. Maximum power and maximum airfoil efficiency criteria have been adopted to design the outer section of the rotor blade, while the constant chord criterion has been used for its inner section. A NACA 0012 airfoil profile has been selected for the rotor blade and the corresponding analytical expressions for the lift and drag coefficients have been taken from Prouty (1986).

3 Mathematical Model of the Self-Excited Induction Generator

The wind turbine drives a three phase self-excited induction generator. Since the stator and rotor windings of the induction generator together with the external load are balanced, a per-phase analysis can be adopted (Fitzgerald *et al.*, 1992). Accordingly, a fixed axis reference system, dq, can be used to determine the governing equations of both the stator and rotor windings (Fitzgerald *et al.*, 1992):

$$\begin{aligned}
v_{1d} &= r_1\,i_{1d} + L_1\frac{d\,i_{1d}}{d\,t} + L_M\frac{d\,i_{2d}}{d\,t},\\
v_{1q} &= r_1\,i_{1q} + L_1\frac{d\,i_{1q}}{d\,t} + L_M\frac{d\,i_{2q}}{d\,t},\\
0 &= r_2\,i_{2d} + L_2\frac{d\,i_{2d}}{d\,t} + L_M\frac{d\,i_{1d}}{d\,t} + p\,\omega_g\,(L_2\,i_{2q} + L_M\,i_{1q})\,,\\
0 &= r_2\,i_{2q} + L_2\frac{d\,i_{2q}}{d\,t} + L_M\frac{d\,i_{1q}}{d\,t} - p\,\omega_g\,(L_2\,i_{2d} + L_M\,i_{1d})\,,
\end{aligned} \tag{5}$$

where r_1 and r_2 are the stator and rotor internal resistances, respectively, while L_1 and L_2 are the corresponding inductances. Moreover, L_M, ω_g, and p represent the mutual inductance, the rotor angular speed, and the number of polar pairs, respectively. The voltages v_{1d}, v_{1q} and the currents i_{1d}, and i_{1q} have no direct physical meaning, although they are related to the phase voltages and currents, as it will be shown lately.

Being the external load represented by a capacity, C, an inductance, L, and a resistance, R, the corresponding governing equations in the dq system of reference are:

$$
\begin{aligned}
v_{1d} &= L\,\frac{d\,i_{Ld}}{d\,t}, \\
v_{1q} &= L\,\frac{d\,i_{Lq}}{d\,t}, \\
C\,\frac{d\,v_{1d}}{d\,t} &= -\frac{v_{1d}}{R_L} - i_{1d} - i_{Ld}, \\
C\,\frac{d\,v_{1q}}{d\,t} &= -\frac{v_{1q}}{R_L} - i_{1q} - i_{Lq}.
\end{aligned} \tag{6}
$$

The dynamic equilibrium of the moving parts of both the wind turbine and the induction generator can be expressed as:

$$\frac{d\,\omega_g}{d\,t} = \frac{1}{J}\left(\frac{Q_T}{\tau} - Q_E\right), \tag{7}$$

where J represents the moment of inertia of all the rotating parts, referred to the electrical generator shaft, while τ and t are the transmission ratio of the gear box and the time. Moreover, Q_E is the rotor electromagnetic torque given by:

$$Q_E = 3\,p\,\left(i_{1d}\,i_{2q} + i_{1q}\,i_{2d}\right). \tag{8}$$

Eqs. (5), (6) and (7) represent a set of nine equations in the nine unknowns i_{1d}, i_{1q}, i_{2d}, i_{2q}, v_{1d}, v_{1q}, i_{Ld}, i_{Lq}, e ω_g, which can be solved, provided that the wind turbine torque is computed by means of Eq. (2). Finally, the phase voltages can be obtained from the unphysical voltages v_{1d} and v_{1q} by means of the following relations:

$$
\begin{aligned}
v_a &= v_{1d}, \\
v_b &= -\frac{1}{2}\,v_{1d} + \frac{\sqrt{3}}{2}\,v_{1q}, \\
v_b &= -\frac{1}{2}\,v_{1d} - \frac{\sqrt{3}}{2}\,v_{1q}.
\end{aligned} \tag{9}
$$

4 Fuzzy Logic System

The Fuzzy Logic System (*FLS*) employs a set of N fuzzy linguistic rules. These rules may be provided by experts or can be extracted from numerical data. In either cases, engineering rules in *FLS* are expressed as a collection of $IF - THEN$ statements. Therefore a fuzzy rule base R containing N fuzzy rules can be expressed as:

$$R = [Rule_1, Rule_2, ..., Rule_i, ..., Rule_N]\,, \tag{10}$$

where the *i-th* rule is:

$$Rule_i : \text{IF}\mathbf{z}(k)\text{ is }\tilde{\mathbf{A}}\text{ THEN }u(k)\text{ is }\beta_i, \tag{11}$$

where k refers to the variable values at time $t = k\,\Delta t$. Moreover, the vector

$$\mathbf{z}(k) = [z_1(k), ..., z_l(k)]^T \tag{12}$$

represents all the l fuzzy inputs to the *FLS*. On the other hand, $u(k)$ represents the fuzzy output of the *FLS*. In the antecedent of the *i-th* rule, the term

$$\tilde{\mathbf{A}} = [\tilde{A}_i^1 ..., \tilde{A}_i^l]^T \tag{13}$$

represents the vector of the fuzzy sets referring to the input fuzzy vector $\mathbf{z}(k)$. The membership functions of both the input vector $\mathbf{z}(k)$ and the vector $\tilde{\mathbf{A}}$ of the fuzzy sets are Gaussian, and assume the following expressions:

$$\begin{aligned} \mu_{zj}(k) &= e^{-1/2\left[(z_j(k)-\hat{z}_j)/\sigma_{zj}\right]^2}, \\ \mu_{\tilde{A}^i_j}(k) &= e^{-1/2\left[(z_j(k)-\hat{A}^i_j)/\sigma_{\tilde{A}^i_j}\right]^2}, \end{aligned} \tag{14}$$

where $\hat{z}_j$ and σ_{zj} are the mean value and the variance of the Gaussian membership function of the *j-th* input, $z_j(k)$. Likewise, $\hat{A}^i_j$ and $\sigma_{\tilde{A}^i_j}$ are the mean value and the variance of the Gaussian membership function of the *j-th* fuzzy set referring to the *i-th* fuzzy rule,$\hat{A}^i_j$. The terms $\hat{z}_j$ and σ_{zj} are known constants, while $\hat{A}^i_j$ and $\sigma_{\tilde{A}^i_j}$ represent the unknown parameters of the *FLS*. As it will be shown, these parameters will be adapted to the controlled wind system by minimizing an appropriate cost function.

The output of the fuzzy controller, $u(k)$, assumes the following expression (Mendel, 1995):

$$u(k) = \frac{\sum_{i=1}^{N} \beta_i \prod_{j=1}^{l} \mu_{Q^i_j}\left[z_{j,max}(k)\right]}{\sum_{i=1}^{N} \prod_{j=1}^{l} \mu_{Q^i_j}\left[z_{j,max}(k)\right]}, \tag{15}$$

where

$$\mu_{Q^i_j}\left[z_j(k)\right] = \mu_{zj}(k)\,\mu_{\tilde{A}^i_j}(k). \tag{16}$$

Moreover,

$$z_{j,max}(k) = \frac{\hat{z}_j\,\sigma^2{}_{zj} + \hat{A}^i_j\,\sigma^2{}_{\tilde{A}^i_j}}{\sigma^2{}_{zj} + \sigma^2{}_{\tilde{A}^i_j}} \tag{17}$$

is the value of the *j-th* input that maximizes Eq. (16). The maximization of Eq. (16) represents the *supremum* operation in the *sup-star* composition of the *i-th* rule (Mendel, 1995).

This fuzzy controller appears to be parameterized by

$$\theta(k) = \left\{\hat{A}^i_j(k), \sigma_{\tilde{A}^i_j}(k), \beta_i(k); i = 1, 2, ..., N; j = 1, 2, ..., l\right\}. \tag{18}$$

In the next section, a procedure that allows an on-line adaptation of the parameters $\theta(k)$ to the controlled wind system will be introduced. The fuzzy logic control system adopted in the present paper is represented in Fig. 1. The fuzzy input vector is defined as:

$$\mathbf{z}(k) = \left[y(k-1), r(k), u(k-1)\right]^T, \tag{19}$$

where $y(k)$ is the output of the plant (controlled variable), $u(k)$ is the control variable (output of the fuzzy controller), and $r(k)$ represents a reference signal for $y(k)$.

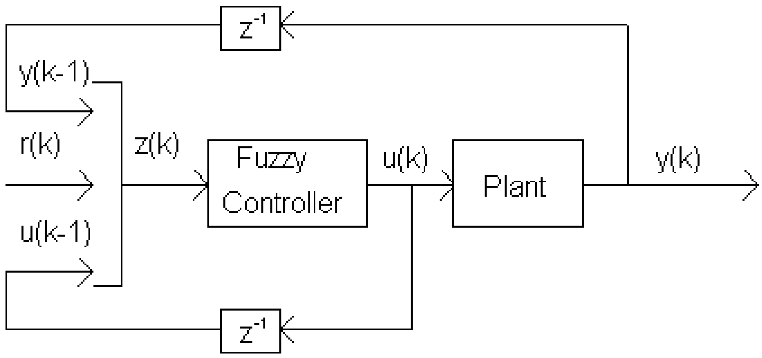

Figure 1: Layout of the fuzzy control system.

5 Estimator-Based Adaptive Fuzzy Logic

In general, an Adaptive Fuzzy Logic (*AFL*) control starts from an initially assumed set of parameters $\theta(0)$, whose only requirement is to stabilize the plant. Then, at each time step, the *AFL* control adapts the set of parameters $\theta(k)$, in order to minimize the cost function:

$$J(k) = \frac{1}{2}\, e_y^2(k), \tag{20}$$

where $e_y(k)$ is the control error defined as:

$$e_y(k) = r(k) - y(k). \tag{21}$$

The control error $e_y(k)$ can be determined only if a deterministic model of the controlled system is available.

In the present paper, we suppose that no *a priori* deterministic model of the controlled system is available. The Estimator-based Adaptive Fuzzy Logic (*EAFL*) control here suggested allows to solve this class of problems. Indeed, instead of deriving the appropriate change in each internal parameter from the control error $e_y(k)$, the *EAFL* refers to an approximate estimation of the control error

$$\hat{e}_y(k) = r(k) - \hat{y}(k), \tag{22}$$

and to the corresponding cost function:

$$\hat{J}(k) = \frac{1}{2}\, \hat{e}_y^2(k). \tag{23}$$

In Eq. (22), $\hat{y}(k)$ represents the estimated value of the output at the time k, to be evaluated. As stated in (Goodwin and Sin, 1984), the present system, can be expressed as follows:

$$y(k) = a_k\, y(k-1) + b_k\, u(k-1), \tag{24}$$

where a_k and b_k represent the time-varying coefficients of model (24). If the controlled plant is observable, then Eq. (24) represents its model in state space notation. In such a case, the model coefficients a_k and b_k are unknown. These coefficients can be on-line estimated by applying the Least Square Algorithm (*LSA*) in recursive form (Goodwin and Sin, 1984; Dambrosio, 1994; Dadone *et al.*, 1998). As a consequence, the basic scheme of the fuzzy control system has to be modified as shown in Fig. 2, where the *LSA* estimator evaluates the coefficients $\hat{a}_k$ and $\hat{b}_k$. Assuming that such coefficients do not change from the time k to the time $k+1$, the estimated

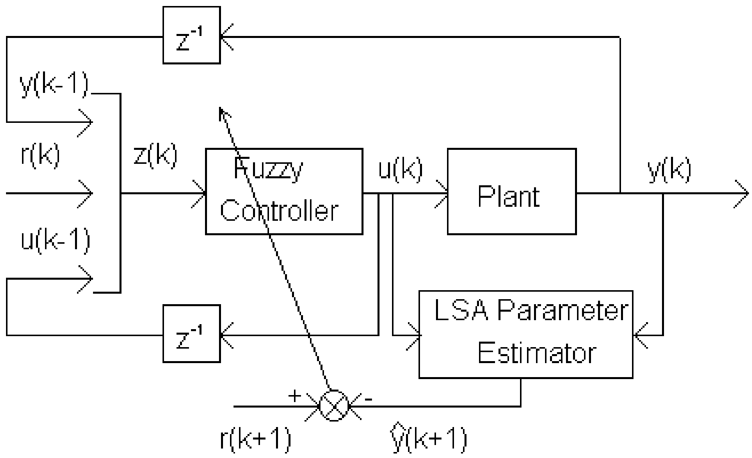

Figure 2: Layout of the fuzzy control system.

model of the controlled system one-step-ahead, i.e., at time $k+1$, assumes the following expression:

$$\hat{y}(k+1) = \hat{a}_k y(k) + \hat{b}_k u(k), \tag{25}$$

which is the output of the *LSA* parameter estimator (Fig. 2).

The signal $\hat{y}(k+1)$ is compared to the reference signal $r(k+1)$ and the difference determines the modification of the fuzzy controller parameters $\theta(k)$. This is implemented by rewriting the cost function $\hat{J}$ at time $k+1$ as:

$$\hat{J}(k+1) = \frac{1}{2}\left\{r(k+1) - \left[\hat{a}_k y(k) + \hat{b}_k u(k)\right]\right\}^2. \tag{26}$$

The minimization of the cost function $\hat{J}(k+1)$ can be easily accomplished by using the gradient descent algorithm as follows:

$$\theta(k) = \theta(k-1) - \eta\,\frac{\partial \hat{J}(k+1)}{\partial \theta}, \tag{27}$$

where the sensitivity derivatives of $\hat{J}(k+1)$ with respect to θ (refer to Eq.18) are given by:

$$\begin{aligned}
\frac{\partial \hat{J}(k+1)}{\partial \beta_i} &= -\hat{b}_k\,\hat{e}_y(k+1)\,\frac{\prod_{j=1}^{l} w_{ij}(k)}{\sum_{i=1}^{N}\prod_{j=1}^{l} w_{ij}(k)}, \\
\frac{\partial \hat{J}(k+1)}{\partial \hat{A}_j^i} &= -\hat{b}_k\,\hat{e}_y(k+1)\,\frac{-\nu_{ij}(k)\sum_{i=1}^{N} c_{ij}\prod_{j=1}^{l} w_{ij}(k)\;[\beta_i - u(k)]}{\sum_{i=1}^{N}\prod_{j=1}^{l} w_{ij}(k)}, \\
\frac{\partial \hat{J}(k+1)}{\partial \sigma_{\tilde{A}_j^i}} &= -\hat{b}_k\,\hat{e}_y(k+1)\,\frac{\sigma_{\tilde{A}_j^i}\,\nu_{ij}^2(k)\sum_{i=1}^{N} c_{ij}\prod_{j=1}^{l} w_{ij}(k)\;[\beta_i - u(k)]}{\sum_{i=1}^{N}\prod_{j=1}^{l} w_{ij}(k)},
\end{aligned} \tag{28}$$

where:

$$\begin{aligned} v_{ij}(k) &= \frac{\hat{A}^i_j - \hat{z}_j}{\sigma^2{}_{\hat{A}^i_j} + \sigma^2{}_{zj}}, \\ w_{ij}(k) &= e^{-1/2\left(\hat{A}^i_j - \hat{z}_j\right)^2 \Big/ \left(\sigma^2{}_{\hat{A}^i_j} + \sigma^2{}_{zj}\right)}. \end{aligned} \tag{29}$$

The coefficient η is the rate of descent which can be chosen arbitrarily. Moreover, c_{ij} is equal to 1 if the *i-th* rule is dependent on the *j-th* input, otherwise it is equal to 0.

6 Results

In the computed application, we have considered a controlled system starting from rest. We have also assumed that the control system reaches a steady-state condition after a starting time interval. During such a steady-state time period, we have hypothesized that appropriate disturbances perturb the system status. The control system acts during the starting time interval in order to guarantee the required time sequence of the system status. Moreover, during the steady-state time period, the control system has to counteract the disturbance effects, in order to preserve the desired steady-state conditions. The aimed target is to control the output voltage and the rotational speed of the induction generator. The control variables are the rotor resistance, r_2, and the transmission ratio, τ, of the gear box connecting the wind turbine to the induction generator. In the presently considered control case, the system disturbances are represented by abrupt changes of the wind velocity and of the resistance load. In particular, we have assumed that the wind velocity instantaneously changes from *10 m/s* to *11 m/s* at time *t=150 s*, while it instantaneously returns to the original value at *t=170 s*. As far as the resistance load disturbance is concerned, we have assumed an instantaneous change from *9 Ω* to *15 Ω* at *t=170 s* and an opposite variation at *t=200 s*.

Figure. 3 shows the time history of the rotational speed, ω_g, of the induction generator, while Fig. 4 presents the corresponding percentage control error, $\Delta\omega\%$. In Fig. 3, dotted and solid lines represent the target and the actual rotational speed, respectively. A quick glance to such figures allows to state that the actual and the target angular speeds are practically coincident during the considered time interval with the obvious exception of small errors during the very first part of the starting time interval. In particular, the disturbance effects, acting during the steady state time interval, appear to be effectively counteracted by the present control system. The only evidence of the disturbance actions is represented by the small spikes in Fig. 4 ($\Delta\omega\% < 0.2\%$) due to the instantaneous variation of the disturbance variables.

Figure. 5 shows the output voltage, V, while Fig. 6 represents the corresponding percentage error, $\Delta V\%$. As shown in Fig. 5, the actual and the target output voltages are practically coincident for most of the considered time interval. Nevertheless, significant differences between the actual and the target voltages can be observed at the beginning of the starting period. Such differences are due to the lack of the auto-excitation of the induction generator at the very beginning of the starting interval. Obviously, such errors cannot be suppressed by any control system. Moreover, Fig. 6 shows two significant spikes, during the steady state time interval, which denote the voltage sensitivity to the instantaneous changes of the resistance load, while no practical effect of the instantaneous changes of the wind velocity can be noticed.

Finally, figures. 7 and 8 show the time variations of the control variables, i.e., the gear box transmission ratio, τ, and the rotor resistance, r_2. These variables vary in accordance to the disturbances, in order to counterbalance their effects. Such an important characteristic proves

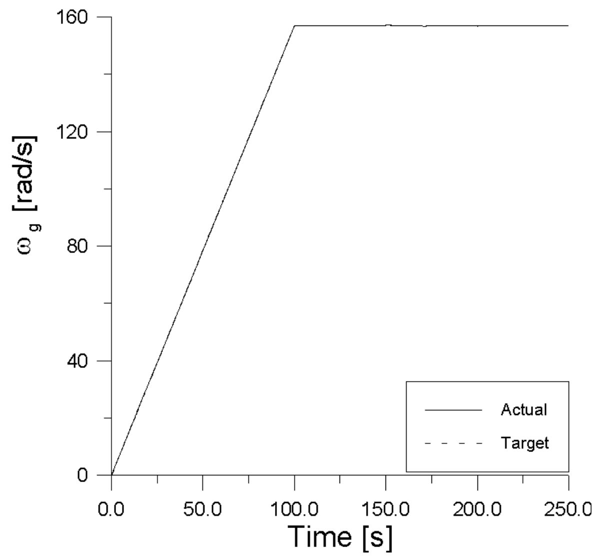

Figure 3: Rotational speed of the induction generator.

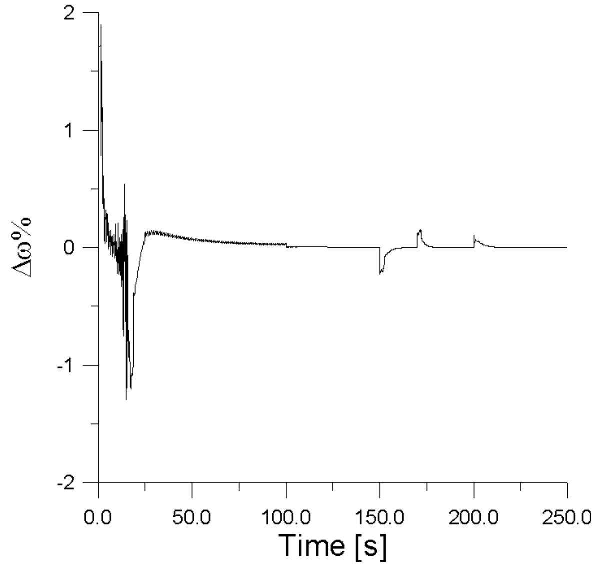

Figure 4: Percentage control error of the output rotational speed.

the adaptive nature of the *EAFL* control technique, which automatically tunes itself in order to take into account all the non-linearities and time-variances of the system under control. In particular, it adaptively annihilates the time delays of the system components. Therefore, we can state that the *EAFL* control system has the property of forcing a physical system characterized by inherently relevant time delays to promptly react to external disturbances.

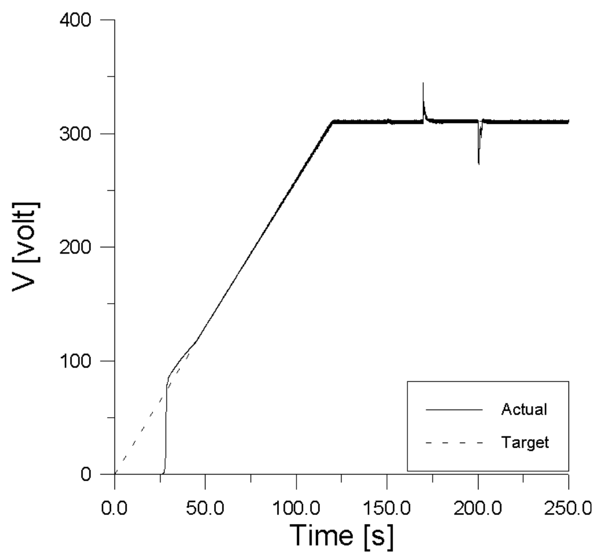

Figure 5: Voltage of the induction generator.

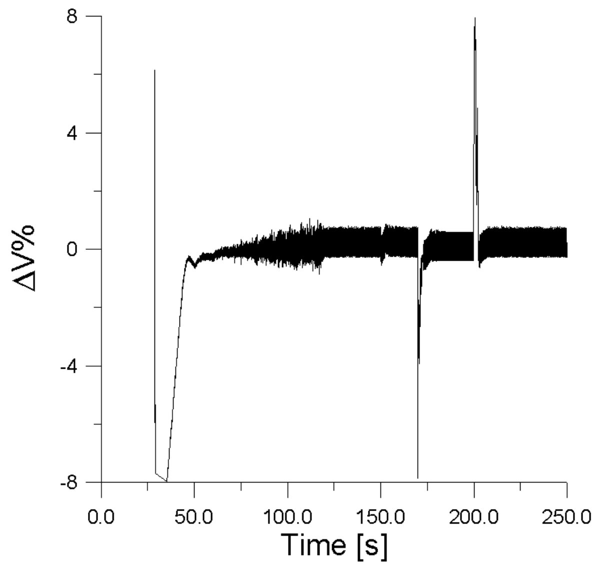

Figure 6: Percentage control error of the output voltage.

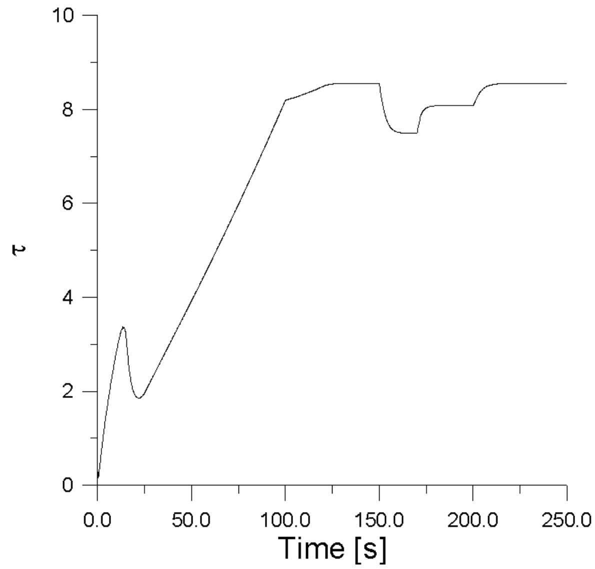

Figure 7: Time history of the transmission ratio (control variable).

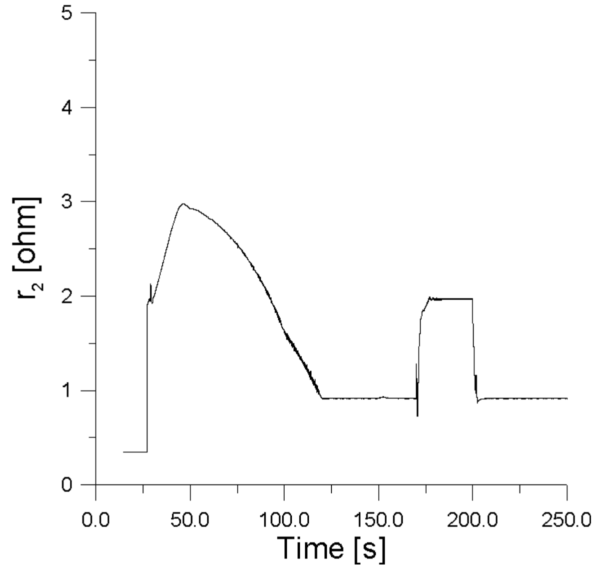

Figure 8: Time history of the rotor resistance (control variable).

7 Conclusions

In the present paper, an Estimator-based Adaptive Fuzzy Logic (*EAFL*) control technique is proposed. The *EAFL* controller is used to control a wind system operating as an isolated electrical power generation station. The wind system is composed by an horizontal-axis three blade wind turbine connected to an electrical induction generator through a gear box. Instead of a real wind system, a numerically simulated wind system is considered and the mathematical models of its components are presented. After a brief review of the fuzzy logic system, the Estimator-based Adaptive Fuzzy Logic controller is described. Its main features are the one-step-ahead estimation of the control error and the on-line optimization of the fuzzy rule base parameters. It is noteworthy, that no a priori deterministic model of the controlled system is required.

We apply the Estimator-based Adaptive Fuzzy Logic controller to control a wind system starting from rest and reaching a steady state condition, which is then perturbed by abrupt changes of the wind velocity and of the electric load. The proposed *EAFL* technique controls the output voltage and the induction generator rotational speed

In all the considered control case the *EAFL* control system proves its ability to adequately control the output variables under the actions of relevant and abrupt disturbances. The control system automatically tunes itself in order to counterbalance all the non-linearities and time-variances of the system under control, thus proving its adaptive characteristic. In particular, it has the property to force a physical system characterized by inherently relevant time delays to promptly react to external disturbances.

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