Adaptive Fuzzy Controller and Adaptive Self-Tuning Controller: Comparative Analysis for the Excitation Control of a Synchronous Generator

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Abstract: - This paper presents a comparative study between an adaptive fuzzy controller and an adaptive self-tuning controller with application to excitation control of a synchronous generator. The adaptive self-tuning controller is based on a dual action, obviously on control input, and also on reference signal. The proposed adaptive fuzzy controller includes a mechanism to adapt one of the tuning parameters. Some comparative studies are performed regarding the performance of a conventional fuzzy PI controller and the designed adaptive fuzzy PI controller (all with application to excitation control of a synchronous generator functioning in active power load regime). Also, to design the adaptive self-tuning controller two situations were considered concern the used parameters estimator: in the first case using a recursive least square error parameters estimator and, in the second, using a parameters estimator based on Givens orthogonal transformation.

Key-Words: - fuzzy controller, adaptive self-tuning controller, identification, modeling and simulation, nonlinear systems, synchronous generator.

1 Introduction

The synchronous generator represents the main equipment in major electric power systems. Due to its active role within the system - being used to supply electric power and to modify the voltage and the circulation of active and reactive power – the synchronous generator shows a capital significance for designers and engineers involved in solving system problems. The present conditions and future trends have determined the intensification of the concerns regarding the utilization of synchronous generator. [2]

Also, in the last years there a trend of an increased interest occurs in the field of using the fuzzy logic in the area of embedded applications. The applicability domain of fuzzy logic is very large, including process control, system identification etc, and so the types of fuzzy controllers are continuously extended. The utilization of self-tuning controller and fuzzy controller has been applied in several industries. An application in power industry, where the adaptive property of these kinds of control strategies is an attractive feature, was considered. The power system is a complex dynamic system, in which the characteristics fluctuate with varying loads and varying generation schedules and the operating point changes too. The classical controllers (PI, PID) cannot maintain the same values of the quality indicators for all these perturbations. This is the reason that adaptive control (self-tuning or fuzzy),

which is adapting to changing system characteristics, has so much potential to improve power system performances. [2][7]

2 Adaptive Fuzzy Controller

There are many approach variants for the tuning problematic of fuzzy adaptive regulators. [6] A first method consists in the use of some scaling factors (time tunable) on the inputs and respectively, on the output of the fuzzy controller. Another method consists in the modifying the membership function allure, through a suitable tuning of their parameter's values. The last mentioned method is the one used in the present paper. In figure 1 is presented the Simulink model of the considered control structure. The system error represents the main variable on which is based on-line tuning of controller's parameter. The implementation and simulation of control structure has been done with Matlab-Simulink, considering the case of a single tunable parameter (the reasoning can be easily generalized also for all other parameters).

The on-line tuning algorithm of a parameter is implemented through a bidecisional procedure, which briefly describes the following tasks (in this case, the 'c' parameter corresponding to the control's variable singletons):

- if the output's error remains in the $[-\alpha, +\alpha]$ range values, it is maintained a constant value c_1 for 'c' parameter (c_1 -experimental off-line determined value)

- if the output's error exceeds the $[-\alpha, +\alpha]$ range values, the 'c' parameter is tuned to a new value c_2, and this value is maintained until the output's error decreases under a β value (β is close to zero).
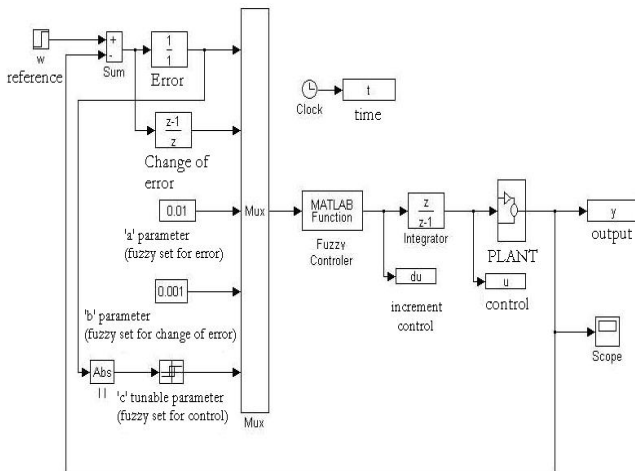

Fig. 1 Simulink model of adaptive fuzzy PI control structure

The study cases showed the fact that the maintenance of 'c' parameter at the new c_2 tuned value (only until the output's error reaches again the $[-\alpha, +\alpha]$ range values) is not sufficient.
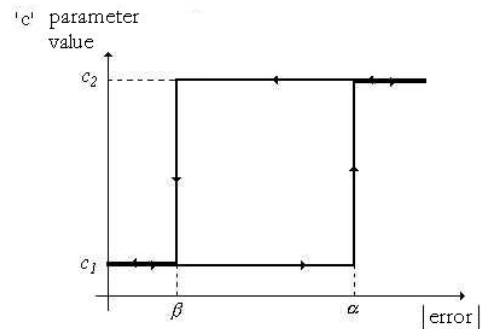

Fig. 2 Evolution of tunable parameter

In this case the control tuned dynamics acting on a too short time period in order to be able to produce significant results in the controlled output. Based on this reason β has a very small chooses value. So, the tuning algorithm presents a similar behaviour as a hysteresis relay element (figure 2).

3 Simulation Studies with Fuzzy Controller

The first study case considered is the one of the conventional fuzzy PI controller. The controller's parameters tuning is performed off-line, afterwards these parameters are being considered constant. In the case of the considered process (the synchronous generator) the operating conditions are the following: at t=10 [s] time moment the mechanical torque presents a 0.2 p.u. increased value. The usage of the tuned parameter considered to be optimal in the case of a previous functioning regime of the synchronous regime (reactive load regime), conducts to totally unsatisfactory results (high amplitude oscillations, considerable long control time and weak command penalty) as depicted in figures 3 and 4.
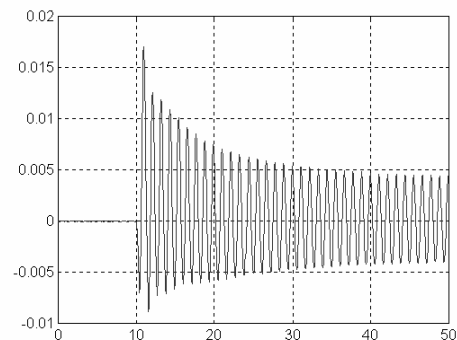

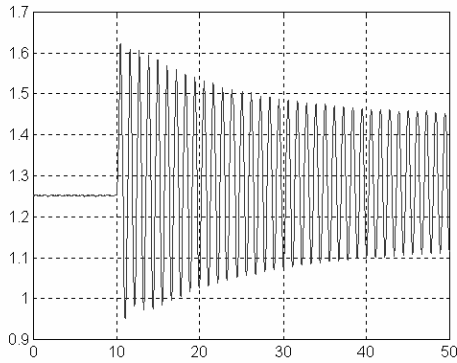Fig. 3 Terminal voltage's variation (controlled output)

Fig. 4 Excitation voltage (controller's output)

Therefore, there must be conducted another tuning of the controller, respectively determination of other tuning parameters set that conducts to an enhancement of the system's performances. The results corresponding to this new parameters set are presented in figures 5 and 6. There can be noticed the fact that the obtained results is much better. Practically, the tune of a single parameter afferent to the controller's output singleton, lead to a considerable modification of the fuzzy controller's dynamics. In figures 5 and 6 can be observed (comparative with the responses presented in figures 3 and 4) an improvement of the control system's performances (shorter control time, small amplitude of the overshoot).
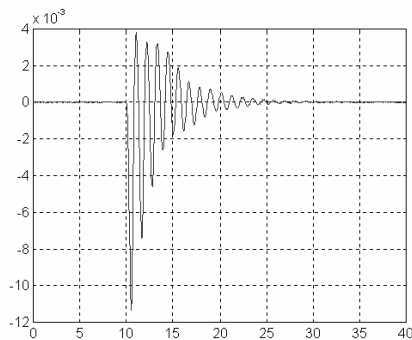

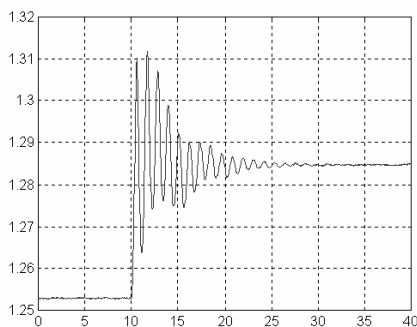Fig. 5 Terminal voltage's variation (controlled output)

Fig. 6 Controller output

In the following study case there is considered the adaptive fuzzy control system (presented in figure 1), where one of the controller's parameter is on-line tuned according to the considerations stated in the 2nd paragraph. In figure 7 is depicted the controlled output in both cases (step input response, and two external perturbations at time 40 sec. and 60 sec.), with and without tuning (the time axis is scaled in seconds). It is considered that any reference to input or output variable is a variation related to the steady state regime.
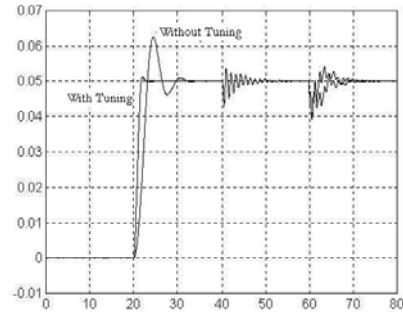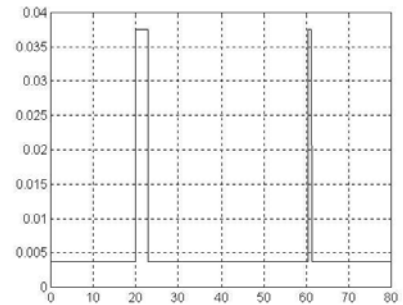

Fig. 7 Controlled outputs

Fig. 8 The variation of tuning parameter 'c'

There can be noticed the higher performances of the adaptive control structure (with on-line tuning of 'c' parameter - figure 8). Although the performances of the PID fuzzy control aren't presented, the mentioned PI fuzzy adaptive controller shows much better performances.

For the considered case, the self-tuning mechanism works especially in the case of an reference modification. As the reference variation grows, we concluded that the role of self-tuning mechanism is more necessary. Also, its role is welcomed in the presence of output perturbations.

4 About on-line Parameters Identification

Assume the linear model of the plant to be in the following form (a discrete transfer function) [3]:

$$H(q^{-1}) = \frac{q^{-1}B(q^{-1})}{A(q^{-1})} = \frac{y(t)}{u(t)}$$ where y, u – process

output, process input and the polynomials
$A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-2} + ... + a_n q^{-n}$,
$B(q^{-1}) = b_0 + b_1 q^{-1} + b_2 q^{-2} + ... + b_m q^{-m}$.

Thus: $$u(t) = \frac{A(q^{-1})y(t)}{q^{-1}B(q^{-1})} \quad (1)$$

In the steady state point, the amplifier gain is $k = \frac{B(1)}{A(1)}$. Therefore $y_r = ku_r$ with y_r, u_r steady state output and input. The starting point for the estimator is the regression matrix equation $\Phi\hat{\theta} = Y$ (Φ measurements matrix, $\hat{\theta}$ vector of estimated parameters) [4], and at a time moment t:

$$q^{-1}\hat{B}(q^{-1})u(t) + [1 - \hat{A}(q^{-1})]y(t) = y(t+1) + \xi(t+1)$$

where ξ - noise (zero means discrete Gaussian process). For $y(t+1)=y(t)+\delta y$, resulting:
$$q^{-1}\hat{B}(q^{-1})u(t) + [1 - \hat{A}(q^{-1})]y(t) = y(t) + \delta y + \xi(t+1) \quad (2)$$

Substituting (1) in (2) and notifying $\Delta y = \delta y + \xi(t+1)$, results

$$q^{-1}\hat{B}(q^{-1})\frac{A(q^{-1})y(t)}{q^{-1}B(q^{-1})} + [1 - \hat{A}(q^{-1})]y(t) = y(t) + \Delta y \quad (3)$$

Dividing relation (3) with $y(t)$, and for a slow change of output ($\frac{\Delta y}{y(t)} \to 0$) results:

$$\hat{A}(q^{-1})B(q^{-1}) = A(q^{-1})\hat{B}(q^{-1}) \quad (4)$$

In a closed loop, relation (4) represents the connection between real parameters and estimated parameters. If at least a correct initialization of parameters estimations was realized ($\hat{A}(q^{-1})\big|_{t=0} = A(q^{-1})\big|_{t=o}$ or $B(q^{-1})\big|_{t=0} = \hat{B}(q^{-1})\big|_{t=0}$) than the estimations will be the same with the real parameters (under a small noise/signal ratio conditions). The relation (4) can be written as $\hat{A}(q^{-1})B(q^{-1})q^{-1} = A(q^{-1})\hat{B}(q^{-1})q^{-1}$ and it can be observed that the ratio: $k(t) = \frac{y(t)}{u(t)} = \frac{q^{-1}B(q^{-1})}{A(q^{-1})} = \frac{q^{-1}\hat{B}(q^{-1})}{\hat{A}(q^{-1})}$ represents the process gain amplification (variable in time for a nonlinear process), and the estimate of this coefficient is equal with the real one. Obtaining such kind of equality it could be considered a criterion for the correctness of the estimator tuning (the selection of the value for the forgetting factor λ).

Moreover, from the relation (4) for $k = \frac{B(1)}{A(1)}$, and taking into consideration that at least in steady state $q^{-1}=1$ and $k = \hat{k}$, results $\hat{A}(1)B(1) = A(1)\hat{B}(1)$ (5)

Relation (5) represents the connection between the real parameters and estimated parameters.

5 Adaptive Self-Tuning Controller

The control strategy of adaptive self-tuning controller is to minimize the cost function:
$$J = E\left\{[y(t+1) - w(t)]^2 + \left[Q'(q^{-1})[u(t) - u_r(t)]\right]^2\right\} \quad (6)$$

where: E denotes the expectation operator, $w(t)$ – reference (imposed plant's output), $u_r(t)$ steady state control (controller output). Minimizing the cost function, by choosing $u(t)$ such that $\frac{\partial J_2}{\partial u(t)} = 0$ and

define $Q(q^{-1}) = \frac{Q'(0)Q'(q^{-1})}{b_0}$ with $Q'(q^{-1}) = \rho_1$ (ρ_1-control weighting [1][5]), results:

$Q(q^{-1}) = \frac{\rho_1^2}{b_0} = \rho$ and the control law becomes:

$u(t) = \frac{w(t) - q[1 - A(q^{-1})]y(t)}{B(q^{-1}) + \rho} + \frac{\rho}{B(q^{-1}) + \rho}u_r(t)$. In the steady state $y(t) = w(t)$ and thus

$$A(q^{-1})w(t) = q^{-1}B(q^{-1})u_r(t).$$

So $u_r(t) = q\frac{A(q^{-1})}{B(q^{-1})}w(t)$ and $u_r(t) = k_f w(t)$ (where

$k_f = \frac{A(1)}{B(1)} = \frac{\hat{A}(1)}{\hat{B}(1)} = \hat{k}_f = \frac{1}{k}$).

Results the control law:

$$u(t) = \frac{-q[1 - \hat{A}(q^{-1})]y(t)}{\hat{B}(q^{-1}) + \rho} + \frac{1 + \rho\hat{k}_f}{\hat{B}(q^{-1}) + \rho}w(t) \quad (7)$$

After the control law is obtained, can noticed that the compensatory parameter related to the reference signal has the following expression (fig. 9): $\hat{K}_f = 1 + \rho\hat{k}_f$ (for $Q(q^{-1})=\rho$). Two parameters estimators have been token into consideration: the classical recursive least square error estimator (RLSE) and a second one non-recursive based on Givens orthogonal transformation.
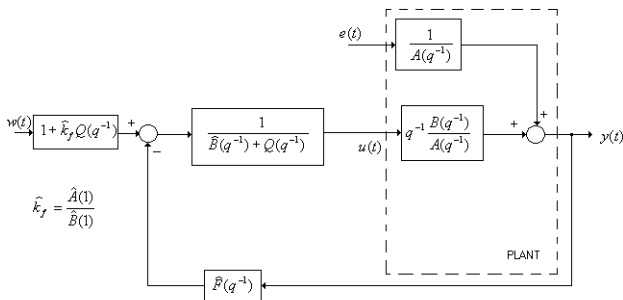
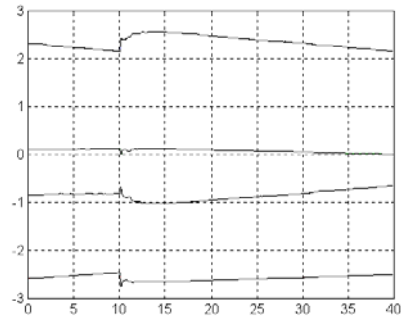Fig. 9 Adaptive self-tuning control system

Fig. 12 *A* polynomial's estimated parameters

6 Simulation Studies with Self-Tuning Controller

The simulation studies concern the active load regime of a synchronous generator (by a 20% mechanical torque change). There are studied the performances of the self-tuning adaptive control system in both cases. All figures have the abscissa axes scaled in time unit (seconds). In the first presented case is used a RLSE estimator. The simulation conditions are: the mechanical torque has a 0.2 [relative units] step deviation; the forgetting factor of RLSE is $\lambda = 0.998$; the process is perturbed by a stochastic noise of zero average and $\sigma^2 = 10^{-8}$ variance; the penalty factor is $\rho = 0.01$.
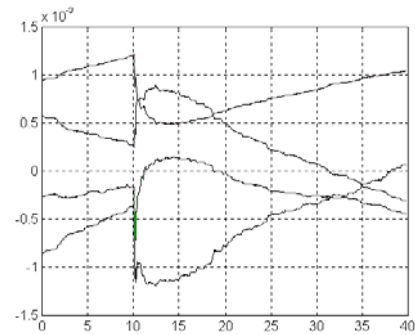

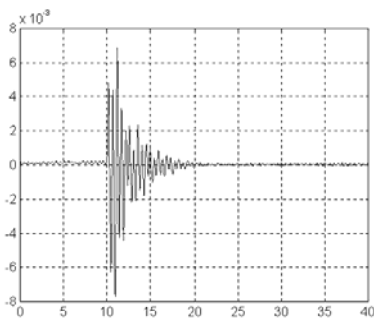Fig. 13 *B* polynomial's estimated parameters

There can be noticed the good performances of the control structure (fig. 10), in the case of an efficient control penalize (fig. 11). In figures 12 and 13 are presented the estimated parameters. Using a parameter estimator based on Givens orthogonal transformation (considering the same tuning parameters values for the controller, respectively the same functioning conditions), the results are presented in figures 14, 15, 16 and 17. There can be noticed the good performances of the control structure. As a fact, the controller output and the plant output in both cases are almost identical, even in the conditions of a different evolution in time of the estimated parameters.
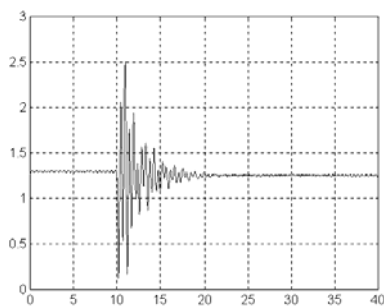

Fig. 10 Output voltage (controlled output)
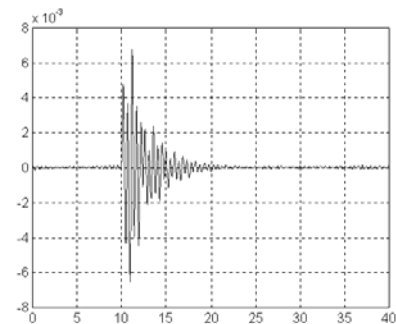

Fig. 11 Controller output

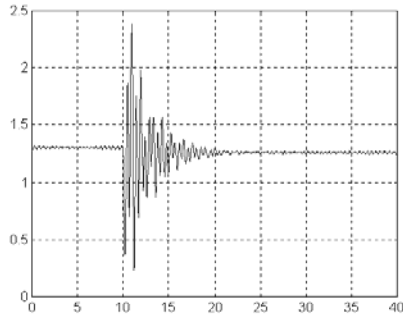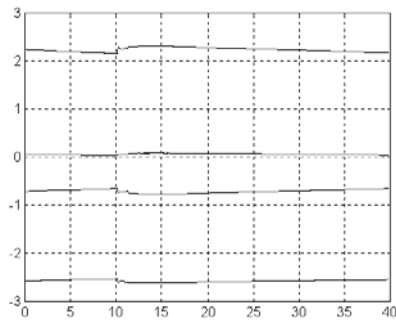Fig. 14 Output voltage (controlled output)

Fig. 15 Controller output
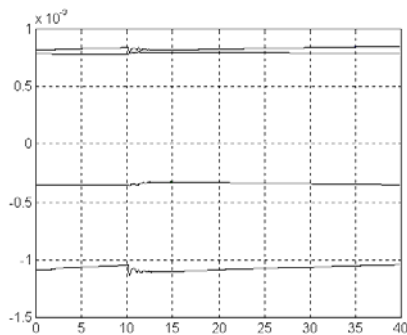

Fig. 16 *A* polynomial's estimated parameters

Fig. 17 *B* polynomial's estimated parameters

7 Conclusion

The performed simulation study cases proved that both adaptive fuzzy controller and adaptive self-tuning controller can be considered as viable solutions for the excitation control of the synchronous generator. The performances of the proposed adaptive fuzzy control structure are compared with the one of a classical fuzzy control structure, however the adaptive tuning mechanism improves the performances in some certain functioning regimes of the synchronous generator.

Also, the simulation studies prove that the performances of the designed adaptive self-tuning controller are not directly dependent to the evolution of estimated parameters. The evolution in time of estimated parameters is not in concordance with the temporal behavior of real parameters, due to cumulated influence of more factors. The type of parameter's estimator used, represents one of those. There can be concluded that, even in the case of different temporal evolution of estimated parameters, due to the different estimation algorithms, the self-tuning control structure's performances are similar.

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