MODDELING, PARAMETERS ESTIMATION AND ADAPTIVE CONTROL OF A SYNCHRONOUS GENERATOR

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Abstract: *This paper presents some considerations regarding the influence of parameters estimation algorithms relative to the performances of an adaptive control system. There were considered two types of parameters estimators: the classical recursive least square (RLS) estimator and respectively, a non-recursive estimator based on Givens orthogonal transformation. All study cases considers as plant a synchronous generator connected to an infinite bus through a long transmission line. There is presented a mathematical model of the considered synchronous generator process and it is also described the implementation algorithm of the non-recursive parameters estimator based on Givens orthogonal transformation. The comparative studies are conducted considering the both cases of an open and a closed loop structure's influence over the parameters estimation. Also a comparative study is done regarding the usage of RLS estimator and respectively the non-recursive estimator based on Givens orthogonal transformation. The simulation results show that the evolution of the estimated parameters doesn't represent a trustful criterion for evaluating the control system performances. Therefore, in the same simulation conditions using different parameters estimators the simulations show different temporal evolutions of the estimated process parameters.*

Keywords: *estimation algorithms, self-tuning control, synchronous machines, least square identification, Givens orthogonal transformation.*

1. INTRODUCTION

The self-tuning control concept is wide spread in several industries. The synchronous generator is an extremely complex dynamic system, which characteristics are in a tight relationship with diverse variables such as: varying loads, varying generation schedules, etc and therefore the operating regime presents a permanent tendency to change. The classical control concept design cannot maintain the same quality of performances for all these variations. This is the reason that promotes the usage of adaptive control, which can easily adapts to permanent changing of system characteristics, and presents a significant potential for the improvement of power system global performances. The on-line estimator of process parameters represents an important component of a self-tuning adaptive control system. The most used and known on-line estimator is the recursive least square (RLS) estimator [1]. The recursive character assures a fast convergence of the estimated parameters values to the true parameters values. The major development of the computational equipment lead to possibility of using also another types of estimators based on non-recursive techniques. From this category belong also the estimators based on orthogonal transformations. The on-line estimation involves the usage of a reduced sampled input-output data set for the considered process. In the case of an open-loop structure, the values of the estimated parameters are identical with the one of the true process parameters. In the case of closed-loop structure (with the process integrated into a control system), in spite of the fact that the real evolution of process parameters is imposed only by the operating regime, the estimated parameters respects a supplementary constraint imposed by the considered control law. In this paper it is proved the fact that the considered types of estimators, and also the estimator's preset parameters lead to different estimation evolutions, with the mention that the control performances are not negatively affected.

In the present paper there were considered two types of estimators: a RLS estimator and an estimator based on Givens orthogonal transformation. There are presented comparative simulation studies, related to a synchronous generator connected to an infinite bus considered as a controlled process. The adaptive controller is responsible for keeping the output voltage constant under normal operating conditions at various load levels. All the simulations were performed in Matlab-Simulink environment. However there are a set of factors that can affect the accuracy of estimation and implicit the control performances. Among this factors can be mentioned: improper design or tuning of the estimator, a high-level stochastic perturbation noise.

2. MODEL OF THE PROCESS - SYNCHRONOUS GENERATOR

The synchronous machine, mostly appearing as synchronous generator, represents the main installation 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. Beginning from the Park's equations, the non-liner model of a synchronous generator connected to an infinite bus through a long transmission line (figure 1) is described by the next ten equations depicted as follows [4] [8]:

$$\frac{d}{dt}(\delta) = \omega_0 s \tag{1}$$

$$M\frac{d}{dt}(s) = -k_d s + T_m - T_e \tag{2}$$

$$T_{d0}^{'}\frac{d}{dt}(e_q^{'}) = v_f - (x_d - x_d^{'})i_d^{'} - e_q^{'} \tag{3}$$

$$T_{d0}^{''}\frac{d}{dt}(e_q^{''}) = e_q^{'} - (x_d^{'} - x_d^{''})i_d - e_q^{''} \tag{4}$$

$$T_{q0}^{''}\frac{d}{dt}(e_d^{''}) = (x_q - x_q^{''})i_q - e_d^{''} \tag{5}$$

$$e_d^{''} = v_d + \gamma_a i_d - x_q^{''} i_q \tag{6}$$

$$e_q^{''} = v_q + \gamma_a i_q + x_d^{''} i_d \tag{7}$$

$$T_e = e_d^{''} i_d + e_q^{''} i_q - \left(x_d^{''} - x_q^{''}\right) i_d i_q \tag{8}$$

$$v_t^2 = v_d^2 + v_q^2 \tag{9}$$

$$T_{ex}\frac{d}{dt}(v_f) = u - v_f \tag{10}$$

$$v_d = v_b \sin\delta + \gamma_e i_d - x_e i_q \tag{11}$$

$$v_q = v_b \cos\delta + \gamma_e i_q + x_e i_d \tag{12}$$

where: $T_{do}', T_{do}'', T_{qo}''$ - time constants; T_{ex} - excitation time constant; δ - rotor angle; ω_0 - synchronous speed; Tm, Te - electric and mechanical torque; i_d, i_q - direct and quadrature axis currents; k_d - damping coefficient; M – inertia; e_q' - quadrature axis transient voltage; e_d'', e_q'' - direct and quadrature axis supratransient voltages; v_d, v_q - direct and quadrature voltages; v_f - field voltage; v_t - terminal voltage (output); v_b - bus voltage; u - control input of excitation voltage; x_d, x_q - direct and quadrature axis reactances; x_d', x_q' - transient reactances; x_d'', x_q'' - subtransient reactances; x_e - transmission system reactance; γ_a - armature resistance; γ_e - transmission system resistance; x_e - transmission system reactance; s – slip;

In this paper the considered synchronous generator is connected to a power system and has a local consumer at the generator terminals (fig.1).

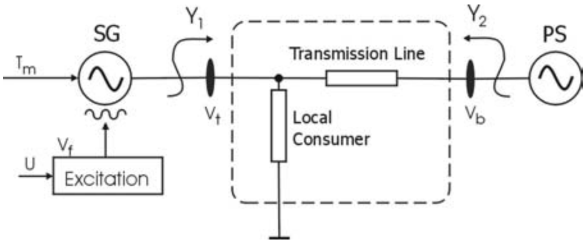

Fig. 1. Synchronous generator connected to a power system

In the fig. 1 the following notations are used: SG – synchronous generator, PS- power system, T_m – mechanical torque, $Y_1=G_1+jB_1$ – transmission network admittance to the SG terminals, $Y_2=G_2+jB_2$ – transmission network SG-PS.

The generalisation of the considered structure consists in introduction in the connection network, beside the transmission line, of a consumer connected at generator terminal [5]. The considered connection network can be treated as a quadripole (fig.2).

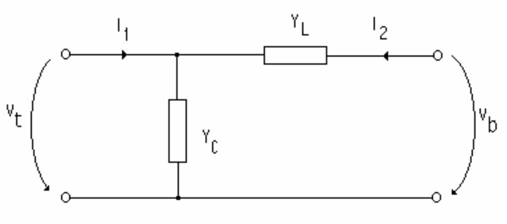

Fig. 2. Equivalent connection network of synchronous generator to a power system

This quadripole (fig.2) is characterised by the following matrix equation:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_L + Y_C & -Y_L \\ -Y_L & Y_L \end{bmatrix} \begin{bmatrix} v_t \\ v_b \end{bmatrix} \tag{13}$$

where: Y_L – transmission line admittance, Y_c- local consumer's admittance.

By noting the admittance (fig. 2) $Y_1=Y_L+Y_C$ (own admittance of the network seen at generator terminals) and $Y_2=-Y_L$ (transfer admittance) and considering that we are only interested by the generator's output current $I=I_1$, the equation which we will use is:

$$I = Y_1 v_t + Y_2 v_b \tag{14}$$

where: $Y_1=G_1+jB_1$ and $Y_2=G_2+jB_2$ (G_1, G_2 – conductance, B_1, B_2 – susceptance; adopted convention: $B_{1,2}<0$ - for inductance).

In this case, by projecting the current I (equation (14)) on d and q axis, the relations that define the i_d and i_q currents will becomes:

$$i_d = G_1 v_d - B_1 v_q - G_2 v_b \sin(\delta) + B_2 v_b \cos(\delta) \tag{15}$$

$$i_q = G_1 v_q + B_1 v_d - G_2 v_b \cos(\delta) - B_2 v_b \sin(\delta) \tag{16}$$

Those relations ((15), (16)) represent the equations that define synchronous generator's connection to power system through a network that includes also a local consumer.

Relations (15) and (16) can be brought to an equivalent form, resulting v_d and v_q voltages:

$$v_d = \frac{1}{B_1^2 + G_1^2}[i_d G_1 + i_q B_1 + (G_1 G_2 + B_1 B_2) v_b \sin(\delta) + \\ + (B_1 G_2 - B_2 G_1) v_b \cos(\delta)] \tag{17}$$

$$v_q = \frac{1}{B_1^2 + G_1^2}[i_q G_1 - i_d B_1 + (B_1 G_2 - B_2 G_1) v_b \sin(\delta) + \\ + (G_1 G_2 + B_1 B_2) v_b \cos(\delta)] \tag{18}$$

The reducing of non-linear model order (from six to four) can be accomplished by neglecting the transient effects in stator and the effects of rotor amortisation windings [4].

Considering these simplifying assumptions, the primary equation set of synchronous generator (1)…(10) is reduced to the following set of equations:

$$\frac{d}{dt}(\delta) = \omega_0 s \tag{19}$$

$$M \frac{d}{dt}(s) = -k_d s + T_m - T_e \tag{20}$$

$$T_{d0}^{'} \frac{d}{dt}(e_q^{'}) = v_f - (x_d - x_d^{'}) i_d - e_q^{'} \tag{21}$$

$$0 = v_d + \gamma_a i_d - x_q i_q \tag{22}$$

$$e_q^{'} = v_q + \gamma_a i_q + x_d^{'} i_d \tag{23}$$

$$T_e = e_q^{'} i_q - \left(x_d^{'} - x_q\right) i_d i_q \tag{24}$$

$$v_t^2 = v_d^2 + v_q^2 \tag{25}$$

completed by equations (17), (18).

Linearising and converting the mathematical model from continuous to discrete time it is obtained a new linear model representing a 4th order transfer function (used only to design the self-tuning controller) [5].

$$H(z^{-1}) = z^{-1}\frac{B(z^{-1})}{A(z^{-1})} = \\ = z^{-1}\frac{b_3 z^{-3} + b_2 z^{-2} + b_1 z^{-1} + b_0}{a_4 z^{-4} + a_3 z^{-3} + a_2 z^{-2} + a_1 z^{-1} + 1} \quad (26)$$

The performed simulations consider the case of the non-linear 6th order model of the synchronous generator (equations (1)…(10), completed with the connection network model – equations (17), (18)), as a process model integrated into the adaptive control system.

3. ABOUT A PARAMETERS ESTIMATOR BASED ON ORTHOGONAL TRANSFORMATION

An important component of an adaptive system is the parameters estimation algorithm of the process model. There exist several basic techniques of parameter identification processing but the most suitable to the circumstances is a least square estimator with a recursive scheme.

This paper will not detail the RLS estimator, this subject being well presented in the technical literature. There is presented a proposed non-recursive estimator based on the Givens orthogonal transformation.
The off-line least square estimator, solves the linear over-determined equation system

$$Y(t) = X(t)\hat{\theta} + \hat{e}(t) \quad (27)$$

the solution is given by relation:
$$\hat{\theta} = [X^T X]^{-1} X^T Y \quad (28)$$

In the linear algebra are well known the following results [9]:

a) $\hat{\theta}$ represents the pseudo-solution of the equation system (27) in terms of the least square method.

b) X^+ defined by relation $X^+ = [X^T X]^{-1} X^T$ is the X matrix's pseudo-inverse.

c) The calculus of the pseudo-inverse based on the definition relation is not always numerical stable, small rounding errors leading to big errors in X^+ or the X matrix can be a badly conditioned matrix and in this case even calculating with a high precision there are obtained false results for the $\hat{\theta}$ estimated.

d) The usage of the orthogonal transformations represents stable numerical calculus procedures for the determination of the pseudo-solution in the terms of least square method.
Solving the equation set (27) using the Givens orthogonal transformation involves the building of an extended X_e matrix obtained from the X matrix by adding a new Y column (corresponding to the output measured terms):

$$X_e = [X\ Y] = \begin{bmatrix} x^T(1) & y(1) \\ x^T(2) & y(2) \\ \dots & \dots \\ x^T(K) & y(K) \end{bmatrix} = \begin{bmatrix} x_e(1) \\ x_e(2) \\ \dots \\ x_e(K) \end{bmatrix} \quad (29)$$

There are considered two rows of the X_e extended matrix, having the following form:

$$x_e(i) = [0, \dots 0, x_{i,i}, \dots, x_{i,k}, \dots, x_{i,n+1}] \quad (30)$$

$$x_e(j) = [0, \dots 0, x_{j,i}, \dots, x_{j,k}, \dots, x_{j,n+1}]$$

On the considered rows in the previous relation is applied the Givens orthogonal transformation defined by:

$$\begin{bmatrix} c & p \\ p & -c \end{bmatrix} \begin{bmatrix} x_e(i) \\ x_e(j) \end{bmatrix} = \begin{bmatrix} x'_e(i) \\ x'_e(j) \end{bmatrix} \quad (31)$$

where the first matrix $Q = \begin{bmatrix} c & p \\ p & -c \end{bmatrix}$ is an orthogonal matrix and the relationship between its elements are given by the equation:

$$c^2 + p^2 = 1 \quad (32)$$

Applying the orthogonal transformation defined by relation (29) conducts to the following expression for the rows $x'_e(i)$ and $x'_e(j)$:

$$x'_e(i) = [0, \dots 0, x'_{i,i}, \dots, x'_{i,k}, \dots, x'_{i,n+1}] \quad (33)$$

$$x'_e(j) = [0, \dots 0, 0, \dots, x'_{j,k}, \dots, x'_{j,n+1}]$$

Analysing the relations (33) there can be noticed that applying the orthogonal transformation sets to zero value the element $x'_{j,i} = 0$. From relations (32) and (33) results the expressions for the elements of the Q matrix:

$$c = \frac{x_{i,i}}{\sqrt{x^2_{i,i} + x^2_{j,i}}} \tag{34}$$

$$p = \frac{x_{j,i}}{\sqrt{x^2_{i,i} + x^2_{j,i}}} \tag{35}$$

Taking into consideration relation (31), by applying the Givens orthogonal transformation, the rows elements $x_e(i)$ and $x_e(j)$ of extended matrix will have the following expressions:

$$x'_{i,k} = cx_{i,k} + px_{j,k} \tag{36}$$

$$x'_{j,k} = px_{i,k} - cx_{j,k} \tag{37}$$

Relations (34) … (37) completely define a Givens orthogonal transformation.

As it can be noticed in relation (31), a calculus step (a Givens rotation) set to zero value the *x(i,j)* term from the X_e extended matrix. Factorisation strategy of the X_e matrix involves the successive setting to zero value of all subdiagonal terms by using successive Givens rotations, starting with the top left corner of X_e matrix and parsing the rows in ascending order.

As a result, the terms are modified in the following parsing order of the *i ,j ,k* index in relations (34) … (37):

$$\begin{gathered} j = 2,\dots,K \\ i = 1,\dots,P\,;\; P = \begin{cases} j-1, & j \le n \\ n, & j > n \end{cases} \\ k = i,\dots,n+1 \end{gathered} \tag{38}$$

Below, is depicted an description example of the adopted strategy for a matrix [4 row x 3 column]:

$$X_e = \begin{bmatrix} x & x & x \\ x & x & x \\ x & x & x \\ x & x & x \end{bmatrix} \rightarrow \begin{bmatrix} x & x & x \\ 0 & x & x \\ x & x & x \\ x & x & x \end{bmatrix} \rightarrow \begin{bmatrix} x & x & x \\ 0 & x & x \\ 0 & x & x \\ x & x & x \end{bmatrix} \rightarrow \tag{39}$$

$$\rightarrow \begin{bmatrix} x & x & x \\ 0 & x & x \\ 0 & 0 & x \\ x & x & x \end{bmatrix} \rightarrow \begin{bmatrix} x & x & x \\ 0 & x & x \\ 0 & 0 & x \\ 0 & x & x \end{bmatrix} \rightarrow \begin{bmatrix} x & x & x \\ 0 & x & x \\ 0 & 0 & x \\ 0 & 0 & x \end{bmatrix}$$

The $\hat{\theta}$ solution is obtained by using the inverse substitution procedure. The inverse substitution procedure, known as the Gauss algorithm used to solve the linear equation systems is characterised by high calculus efficiency, the estimated parameters order being from $\hat{\theta}_n$ to $\hat{\theta}_1$. For the considered process model described by relation (26), the order of estimated parameters will be $\hat{b}_3, \hat{b}_2, \hat{b}_1, \hat{b}_0, \hat{a}_4, \hat{a}_3, \hat{a}_2, \hat{a}_1$.

The estimation algorithm using the Givens orthogonal transformation is based on the property of this transformation that leaves "*opened*" the X_e matrix. This means, that the adding of a new row to the X_e extended matrix (on which already has been applied an orthogonal transformation in order to set to zero value the sub diagonal elements) assumes setting to zero only the elements of the new row (using the transformation relations (34)…(37)).

There can be noticed that the calculus of the $\hat{\theta}$ solution doesn't require the presence of the last X_e matrix's rows (rows that confer the over-determination property to equation system). This fact assures the possibility to permanently use the location of the X_e matrix's last row for the adding of a new row (the equation corresponding to the new measured data set). Therefore, can be achieved a significant estimation speed increase, and also the algorithm can be more easily software implemented. Any new sampled data set (a input-output pair values *(u,y)*), involves only the replace of the last row of the already transformed matrix and the setting to zero the sub diagonal elements by an orthogonal transformation, requiring a reduced time and calculus effort. Such estimator can be used for online parameter estimation into an adaptive system.

The estimation algorithm used in the present paper, assumes the following steps:

Step 1: There is initialised the X_e extended matrix with the first sampled data set *(u(t), y(t))*, so that the number of the rows is at least equal with number of the estimated parameters.

Step 2: It is calculated X'_e using the Givens orthogonal transformation

Step 3: At the *t+1* time moment there is sampled the next data set *(u(t+1), y(t+1))* and is constituted the row $x_e(t+1)$. This new row will replace the last row (corresponding to the previously *t* time moment) from the X'_e matrix. There is applied the orthogonal transformation in order to set to zero value the sub diagonal elements of this new row, leading to a new X'_e transformed extended matrix.

Step 4: Through inverse substitution is solved the equivalent obtained equation system, resulting the estimation vector $\hat{\theta}(t+1)$ at $t+1$ time moment.

Step 5: Jump to the step 3.

4. STUDY CASES

4.1 *Open-loop parameters estimation*

The first study case takes into account the process parameters estimation in open loop (using RLS estimator, respectively the parameters estimator based on Givens orthogonal transformation). The considered operating conditions are: active power load - by modifying mechanical torque, respectively modifying local consumer's admittance (fig.3.a). Variations of parameters estimation are presented in fig.3.b. (with RLS estimator).

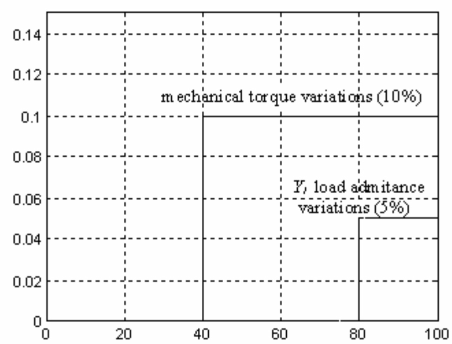

Fig.3.a. Variation of input perturbation

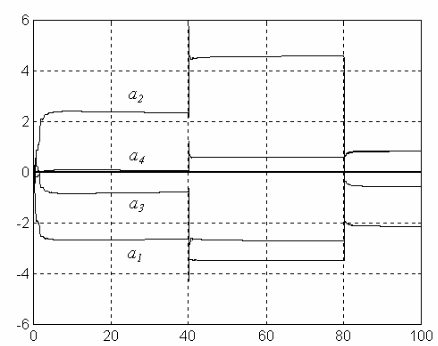

Fig.3.b. Process estimated parameters obtained with a least squares estimator

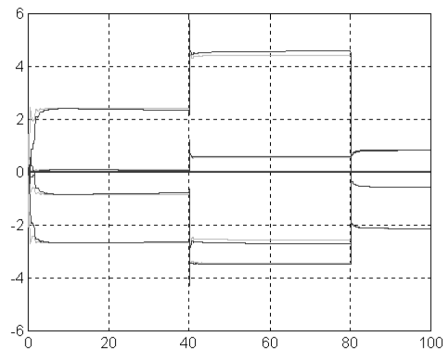

Fig.3.c. Process estimated parameters obtained with a least squares estimator, respectively with an estimator based on Givens transformation – comparative presentation

The B polynomial's *b0, b1, b2, b3* parameters have very small values (close to zero) and from this reason they are not depicted explicitly on the figure 3.b. In figure 3.c there are depicted the both sets of estimated parameters, obtained using a RLS estimator, respectively an estimator based on the Givens orthogonal transformation (the two estimation set results are almost overlapped). In all pictures, the abscissa axes are scaled in time units [seconds].

If the process is into an open loop, for a specific steady state regime and in the absence of the perturbations, the evolutions of parameter's estimation are constant (figure 3.b and 3.c).

As a conclusion, the estimation process into an open loop doesn't depend on the estimator type. The parameter values are changed only in case of a modification of the steady state regime. Between the two modifications of the steady state regime (at $t=40$ sec. and $t=80$ sec. time moment), the estimated parameters have constant values (as it can be expected).

4.2 *Closed-loop parameters estimation and control*

In this case the process (synchronous generator) is considered to be included into a self-tuning control system. The design of such self-tuning controller starts with minimisation of a cost function. This kind of function (usual mentioned in references [1][2][3][6]) corresponding to the minimum variance strategy, is described by relation:

$$J_1 = E\left\{\left[y(t+1) - w(t)\right]^2 + \left[Q'\left(z^{-1}\right)u(t)\right]^2\right\} \quad (40)$$

where: *y(t)* – process output , *w(t)* –reference input, *u(t)* – process input (self tuning controller output), *E* – mean operator, Q' – a suitable chosen polynomial in idea to achieve the imposed performances.

Results the following particular control law (designed based on process linear model describes by relation 26):

$$u(t)=\frac{w(t)+\hat{a}_1y(t)+\hat{a}_2z^{-1}y(t)+\hat{a}_3z^{-2}y(t)+\hat{a}_4z^{-3}y(t)}{\hat{b}_0+\hat{b}_1z^{-1}+\hat{b}_2z^{-2}+\hat{b}_3z^{-3}+Q(z^{-1})} \quad (41)$$

A general form considered for the polynomial $Q(z^{-1})$ is

$$Q(z^{-1})=\rho(1-z^{-1}) \quad (42)$$

Such form is adopted in order to insert an integrator into the closed-loop, with the goal to eliminate the steady-state error (ρ is the control penalty factor used to penalize an excessive control) [3][4].

4.2.1 Using RLS estimator

These study cases are focused on temporal evolution of process parameters estimations operating under the new conditions imposed by the controller closed-loop.

A first study case is described for an active power load, under the following operating conditions: 20% step increasing of mechanical torque *Tm*, forgetting factory of least square estimator is $\lambda = 0.998$, the process is affected by stochastic noise of zero average and variance $\sigma^2 = 10^{-6}$, control penalty factor is $\rho = 0.005$.

There can be noticed out standing performances of the controlled output (fig.4.a). Estimated parameters are presented in fig. 4.c, 4.d and we can distinguish a different evolution in this case (estimation into an closed-loop) comparatively with the estimations into an open-loop (both corresponding to an active power load).

Considering identical simulation conditions as in the previous case and modifying only the ρ controller parameter in consensus of a growth of control penalisation ($\rho = 0.01$), the results are presented in fig. 5.a…5.d. Obviously the controller’s output variance decreases (fig. 5.b). It can be noticed similar outstanding performances (fig.5.a), even in the conditions of different evolutions of process estimated parameters (fig.4.c, d comparative with 5.c, d).

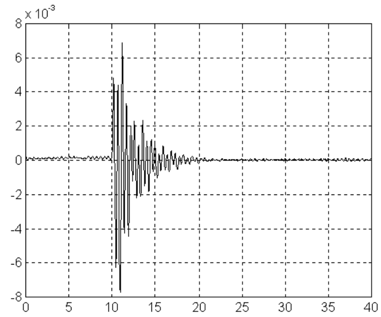

Fig. 4.a. Terminal voltage deviation (controlled output)

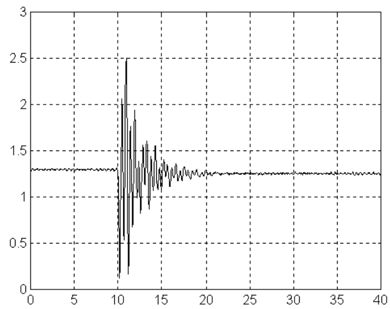

Fig. 4.b. Excitation voltage (controller output)

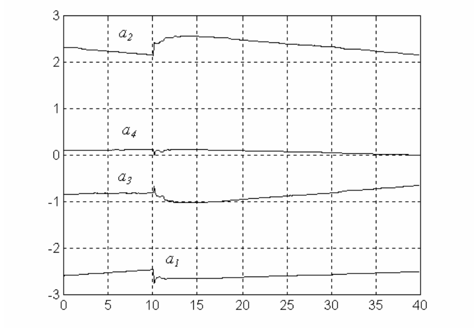

Fig. 4.c. Estimated parameters (coeff. of *A* polynomial)

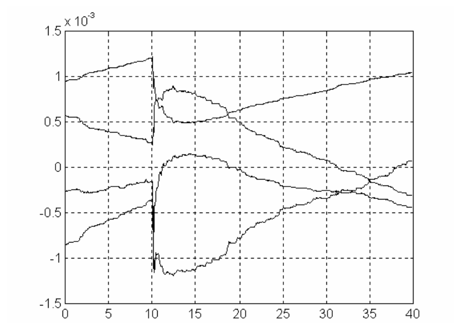

Fig. 4.d. Estimated parameters (coeff. of *B* polynomial)

Also we see that the temporal evolution of process estimated parameters (specially reported to *B* polynomial’s coefficients), is affected by tuned parameters of self-tuning controller.

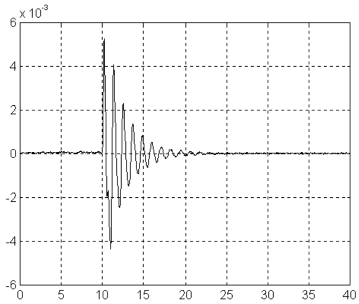

Fig.5.a. Terminal voltage deviation (controlled output)

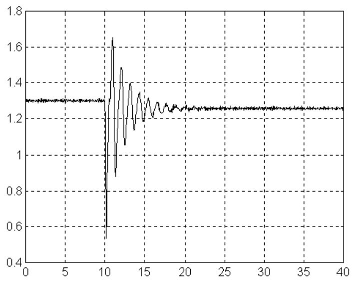

Fig. 5.b. Excitation voltage (controller output)

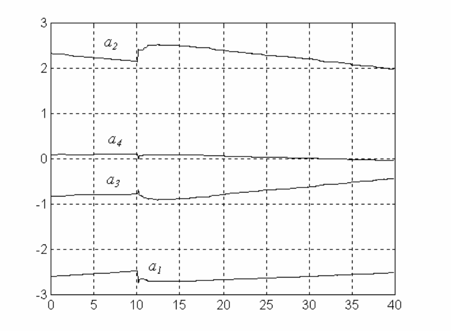

Fig.5.c. Estimated parameters (coeff. of *A* polynomial)

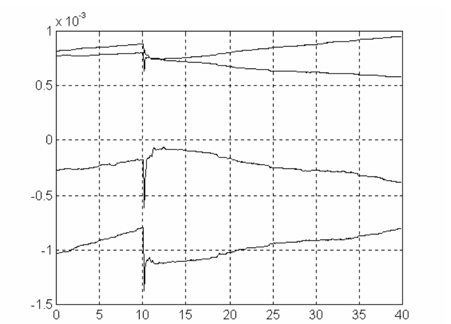

Fig.5.d. Estimated parameters (coeff. of *B* polynomial)

In the context of a sufficiently high control penalty factor, the influence to the evolution of those estimates is quite reduced. Also in the of different process parameter estimation evolution it can obtain similar performances of controlled output. Practically, a sufficient highly control penalty factor ρ shields up the performances of controlled output to the inherent estimations fluctuations [6][7].

For the same preset values of controller's parameters as in the previous case, but considering a higher stochastic noise level ($\sigma^2 = 10^{-4}$), the simulation results are presented in the figure 6.a…6.d. The overall results are good, proving a high robustness and stability of the controller even under the action of a high level stochastic noise. As it can be noticed the parameter estimations are intensively influenced by the noise, without altering the controller's performances.

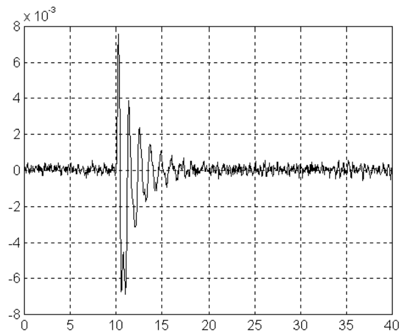

Fig.6.a. Terminal voltage deviation (controlled output)

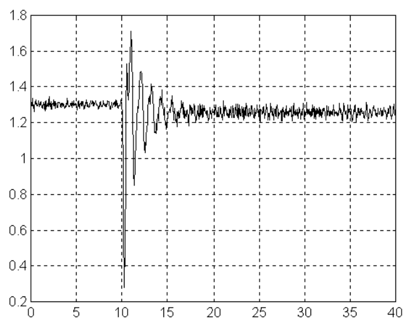

Fig. 6.b. Excitation voltage (controller output)

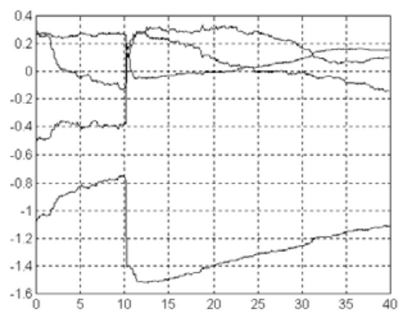

Fig.6.c. Estimated parameters (coeff. of *A* polynomial)

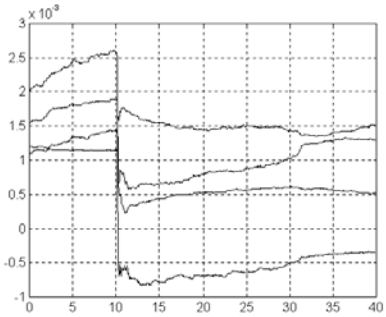

Fig.6.d. Estimated parameters (coeff. of *B* polynomial)

4.2.2. Using parameters estimator based on Givens orthogonal transformation

In the same operating conditions as in the first case using de RLS estimator (20% step increasing of mechanical torque *Tm*, no forgetting factory, stochastic noise of zero average and variance $\sigma^2 = 10^{-6}$, control penalty factor $\rho = 0.005$), the simulation is redone using a non-recursive parameters estimator based on Givens orthogonal transformation. The control performances using the estimator based on Givens orthogonal transformation (fig.7.a…d) are similar with the ones obtained by the adaptive control system using the RLS estimator, in the conditions of different temporal evolutions of estimated parameters.

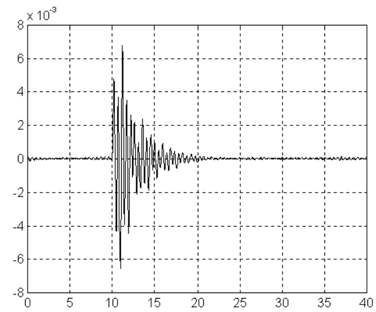

Fig.7.a. Terminal voltage deviation (controlled output)

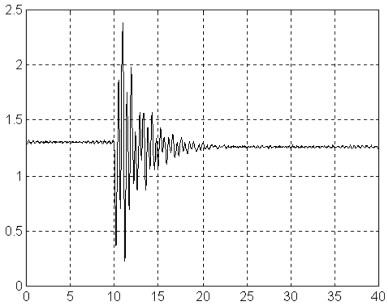

Fig.7.b. Excitation voltage (controller output)

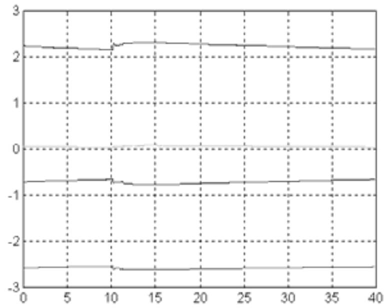

Fig.7.c. Estimated parameters (coeff. of *A* polynomial)

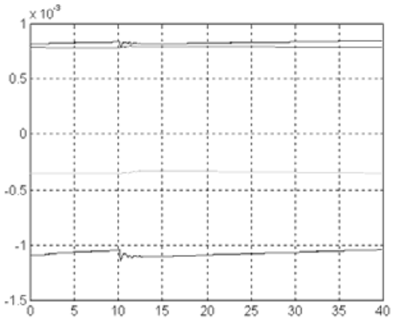

Fig.7.d. Estimated parameters (coeff. of *B* polynomial)

Such a non-recursive estimator based on Givens orthogonal transformation assures o high numerical stability.

If the noise level is higher ($\sigma^2 = 10^{-4}$), the evolution of parameters estimations is changed (fig.8.c, d) but the performances of the adaptive control system (variance of the controller output and variance of the controlled output) are maintained (fig. 8.a, b).

A large number of other simulation studies (not presented in this paper) were performed considering various operating conditions for synchronous generator and all conducted to the same conclusions.

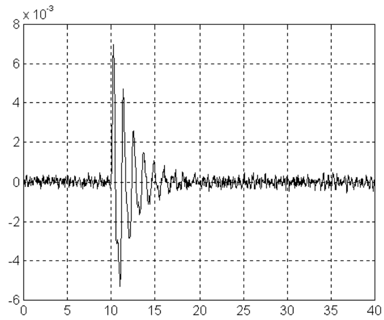

Fig.8.a. Terminal voltage deviation (controlled output)

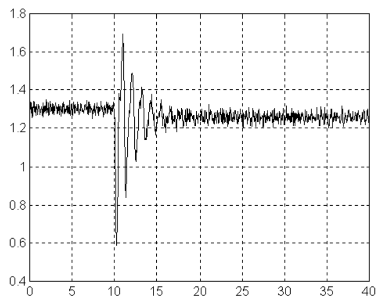

Fig. 8.b. Excitation voltage (controller output)

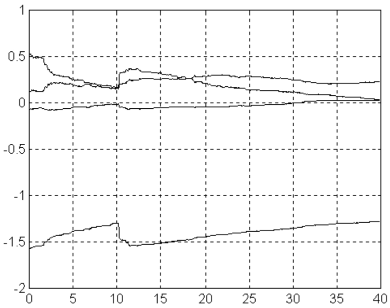

Fig.8.c. Estimated parameters (coeff. of *A* polynomial)

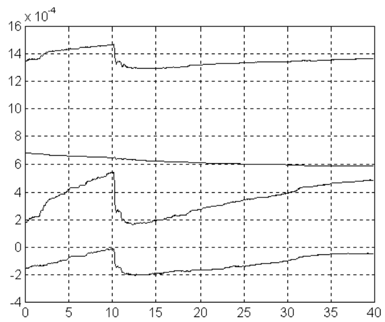

Fig.8.d. Estimated parameters (coeff. of *B* polynomial)

5. CONCLUSION

The paper presents a mathematical model of a synchronous generator connected to an infinite bus (considered as the controlled plant) and a non-recursive estimator algorithm based on Givens orthogonal transformation, in the context of a self-tuning adaptive control system. The comparative studies are conducted regarding the usage of classical RLS estimator and respectively the proposed estimator based on Givens orthogonal transformation. The process estimated parameters present different temporal evolutions in relation with specifically operating conditions, types of parameters estimators, stochastic noise levels and different preset values of self-tuning controller's parameters. The simulation results lead to the conclusion that the evolution of the estimated parameters is not a conclusive criterion regarding the control performances. Therefore, in the same operating conditions and using different parameters estimators, the simulations show different temporal evolutions of the estimated parameters, but the overall performances of the adaptive control doesn't present significant changes. The proposed non-recursive estimator based on Givens orthogonal transformation assures o high numerical stability.

The results were validated through computer simulations for the particularly case of a synchronous generator, but they can be extrapolated for any other process included into an adaptive control system.

6. REFERENCES

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