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# Adaptive Optimal LQ Regulator for Linear Systems Applied to Discrete Power System Model

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**ABSTRACT:** The proposed control strategy of this paper solves the adaptive LQ optimal regulation problem for continuous-time systems, by the utilization of, a new class of multirate controllers, called TPMCs (two-point-multirate controllers). In this type of controller, the control is constrained to a certain piecewise constant signal, and the controlled plant output is detected many times over a fundamental sampling period. The adaptive control strategy suggested here relies on solving the continuous LQ regulation problem. On the basis of this strategy, the original problem is reduced to an associate discrete-time LQ regulation problem for the performance index, with cross-product terms, for which a fictitious static-state feedback controller needs to be computed. The present technique essentially resorts to the computation of simple gain controllers rather than to the computation of state observers, as compared to other known techniques. The proposed adaptive scheme is readily applicable to non-minimum phase systems and to systems that do not possess the parity interlacing property (i.e., they are not strongly stabilizable). The discrete linear open-loop system model under consideration derived from the associated continuous 3th-order linearized open-loop model of an actual working power system, consisting by an 160 MVA synchronous generator and supplying power to an infinite grid, through a step-up transformer and its adequate transmission line. Through the obtained pertinent simulation results, the validity and practical usefulness of this design technique is fully assessed.

**KEYWORDS**: Adaptive Control, optimal multirate control , LQ regulator, parameter estimation, power system.

## I. INTRODUCTION

In the present work, the adaptive optimal LQ regulation problem for continuous-time systems is solved using an alternative approach, which is based on a control strategy that is essentially a combination of the control strategies reported in [10]. We refer to this novel control strategy as a two-point-multirate controller (TPMRC). TPMRCs constitute a typical control strategy, wherein control updates are done at different rates than output samples [11].

The dynamic stability enhancement of an open-loop power system model, linearized about its nominal operating point, may be achieved by designing a suitable excitation controller and thus obtaining a closed-loop system with desired dynamic stability characteristics. The actual design of such controllers can be accomplished by using various modern control methods. Among them, linear quadratic (LQ) optimal control methods have received considerable attention in the past [2-9,13]. However, most of these optimal control techniques, suffer from several serious disadvantages. It is pointed out that the used technique for TPMRCs [10,11,12], transforms the original LQ regulation problem to an associated discrete-time LQ regulation problem for the performance index, with crossed product terms. Concerning this last problem, the necessary computations are performed for a fictitious static state feedback controller. In addition, this technique offers more flexibility in choosing the sampling rates and provides a better power design computed method.

On the other hand, multi-rate controllers are in general time-varying. Thus, multi-rate control systems can achieve what single-rate cannot (e.g. gain improvement, simultaneous stabilization and decentralized control). Finally, multi-rate controllers are normally more complex than single-rate ones; but often they are finite-dimensional and periodic in a certain sense and hence can be implemented on microprocessors via difference equations with finitely many

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coefficients. Therefore, just as single-rate controllers, the multi-rate controllers do not violate the finite memory constraint of the microprocessors. In particular, the control strategy presented here is essentially a combination of the control strategies reported in [11,10]. The control is constrained to a certain piecewise constant signal, while the controlled plant output is detected many times over a fundamental sampling period. The proposed adaptive control strategy relies on solving the continuous LQ regulation problem.

In the present work, the adaptive optimal LQ regulator via a TPMRC scheme is used, to design a desirable excitation controller for a turbogenerator system [14,15], in order to enhance its dynamic stability characteristics. The particular turbogenerator studied in this paper is a 160 MVA unit with excitation voltage, supplying power to an infinite grid via a step-up transformer and a high-voltage transmission line.

The design of the digital controller, which leads to the associated discrete closed-loop control system, in order to achieve the enhanced dynamic stability characteristics, is accomplished by properly applying the presented adaptive optimal LQ regulator, by using the TPMRCs technique.

## II. PRELIMINARIES AND PROBLEM FORMULATION

Consider the continuous-time, linear time-invariant single-input, single-output system described in state space by the following equations:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + B\mathbf{u}(t)\,, \tag{1a}$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) \tag{1b}$$

where $\mathbf{x}(t) \in R^n, \mathbf{u}(t) \in R\ and\ \mathbf{y}(t) \in R$ are the state, control and output signals, respectively and **A**, B, C, D are real matrices having appropriate dimensions. With regard to system (1), we make the following assumption [2,9].

*Assumption 1.* System (1) is controllable (can be stabilized), observable (can be detected), and of known order *n*. The following definition will be useful in the sequel.

*Definition 1.* The generalized reachability Grammian? of order N on the interval [0, $T_o$] is defined as:

$$\mathbf{W}_N(T_0,0)=T_N^{-1}\sum_{\mu=0}^{N-1}\delta_\mu\delta_\mu^T \quad \text{where:} \quad T_N = \frac{T_0}{N}, \quad \delta_\mu = \hat{\mathbf{A}}_c^{(N-\mu-1)}\hat{\mathbf{B}}_{T_N}, \quad \hat{\mathbf{A}}_c = \exp(\mathbf{A}T_N), \quad \hat{\mathbf{B}}_{T_N} = \int_0^{T_N}\exp(\mathbf{A}\delta)\mathbf{B}d\lambda$$

Let $p_N$ be the rank of $\mathbf{W}_N(T_O, 0)$. As $\mathbf{W}_N(T_O, 0) \geq 0$, we can always find (perhaps not uniquely) an n x $p_N$ full rank matrix $\mathbf{B}_n$ such that:

$$\mathbf{B}_n\mathbf{B}_N^T = \mathbf{W}_N(T_o,0) \tag{2}$$

The input of the plant is constrained to the following piecewise constant control:

$$(kT_o + \mu T_N + \zeta) = \Pi_\mu\hat{\mathbf{u}}(kT_o) \equiv T_N^{-1}\delta_\mu^T\mathbf{B}_N^r\hat{\mathbf{u}}(kT_o)\,, \quad \hat{u}(kT_o) \in \Re^{p_N}$$

for $t = kT_0 + \mu T_N + \zeta$; $\mu = 0,1,\ldots, n — 1$; $k \geq 0$; and $\zeta \in [0,T_N)$.

The output of the plant is detected at every $T_M = T_o/M$, such that:

$$y(kT_o + \rho T_M) = \mathbf{c}^T\mathbf{x}(kT_o + \rho T_M) \tag{3}$$

where $M \in Z^+$ is the output multiplicity of the sampling.

It is worth noticing that here we assume, in general, that $M \neq N$, or in other words that the multirate sampling of the

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plant input and output may be performed at a different rate.

The sampled values of the plant output obtained over [$kT_0$, $(k + 1)T_0$) are stored in the M-dimensional column vector $\hat{\gamma}(kT_o)$ of the form:

$$\hat{\gamma}(kT_o) = \left[ y(kT_o)\, y(kT_o + T_M) \ldots y(kT_o + (M-1)T_M) \right]^T \tag{4}$$

The vector $\hat{\gamma}(kT_o)$ is used in the control law of the form:

$$\hat{\mathbf{u}}\left[(k+1)T_o\right] = \mathbf{L}_u \hat{\mathbf{u}}(kT_o) - \mathbf{K}\hat{\gamma}(kT_o) \tag{5}$$

$\mathbf{L}_u \in \Re^{p_{NxM}}, \mathbf{K} \in \Re^{p_{NxM}}$. where:

The adaptive LQ regulation problem treated in the present work can be presented as the following:

Find a TPMRC (Two-point-multirate controller), that, when applied to system 1, minimizes the following cost criterion [1,2]:

$$J = \frac{1}{2}\int_0^{\infty} (qy^2(t) + ru^2(t))dt \tag{6}$$

where, for the design constants q and r, we have $q \geq 0$, $r > 0$ and $(\mathbf{A}, qcc^T)$ is an observable pair.

## III. SOLUTION OF THE LQ OPTIMAL REGULATION PROBLEM APPROPRIATE FOR THE ADAPTIVE CASE

In order to obtain a valid solution for the aforementioned TPMRC-based LQ optimal regulation problem, that will be more appropriate for application to systems with unknown parameters, we slightly modify our control strategy as shown in fig 1. In particular, we introduce in the control loop the persistent excitation signal υ(t), which is defined as [6,7,8]:

$$\upsilon(t) = \mathbf{q}^T(t)\mathbf{v}, \quad \mathbf{q}^T(t) = \left[q_0(t), \ldots, q_{N-1}(t)\right] \tag{7}$$

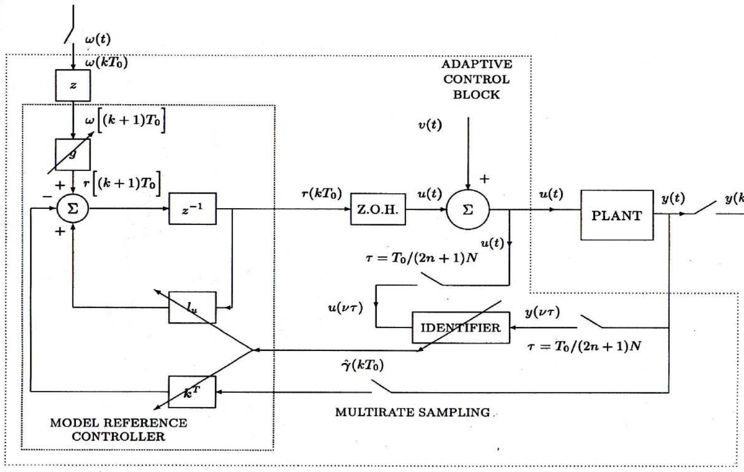


Fig. 1 The structure of the adaptive control system.

Here, q(t) is the $T_N$-periodic vector function with elements having the form:

$$q_i(t) = q_{i,\mu} \;\; for\; t \in \left[\mu T_N, (\mu+1)T_N\right], \;\; i=0, 1,\ldots,N-1, \;\; \mu=0, 1,\ldots,N-1 \tag{8}$$

where $q_{i,\mu}$ is a constant taking the following values:

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$$q_{i,\mu} = \begin{cases} 1, & for\ \mu = i \\ 0, & for\ \mu \neq i \end{cases} \tag{9}$$

It is pointed out that v is as yet unknown. We remark that the additive term $\upsilon(t) = q^T(t)v$, in the input of the continuous-time system is used only for identification purposes and, as it will be shown later, it is selected so as not to influence the LQ regulation problem.

In the sequel, the nature of the control law Eq. 5 will be explained. To this end, we establish the following fundamental theorems.

Theorem 3.1. The following basic formula of the multirate-output sampling mechanism holds [8,9]:

$$\mathbf{Hx}\left[(k+1)T_o\right] = \hat{\boldsymbol{\gamma}}(kT_o) - \mathbf{D}\hat{\mathbf{u}}(kT_o),\ k \geq 0\,, \tag{10}$$

where $\mathbf{H} \in \Re^{Mxn}$ *and* $\mathbf{D} \in \Re^{Mxp_N}$ have the following forms:

$$\mathbf{H} = \begin{bmatrix} \mathbf{c}^T(\hat{\mathbf{A}}^M)^{-1} \\ \mathbf{c}^T(\hat{\mathbf{A}}^{M-1})^{-1} \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{c}^T\mathbf{A}^{-1} \end{bmatrix}, \quad \mathbf{D} = \begin{bmatrix} \mathbf{c}^T\hat{\mathbf{B}}_0 \\ \mathbf{c}^T\mathbf{B}_1 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{c}^T\hat{\mathbf{B}}_{M-1} \end{bmatrix}, \text{ where: } \hat{\mathbf{B}}_\rho = \mathbf{B}_M^*(\rho) - \hat{\mathbf{A}}^{\rho-M}\mathbf{B}_N,\ \rho = 0,1,...,M-1. \tag{10}$$

Using the above definitions and after algebraic manipulation, the matrix gain **K** will obtain the following form [11]:

$$\mathbf{K} = \left[\left(\tilde{\mathbf{R}}_N + \mathbf{B}_N^T\mathbf{P}\mathbf{B}_N\right)^{-1}\left(\tilde{\mathbf{G}}_N^T + \mathbf{B}_N^T\mathbf{P}\boldsymbol{\Phi}\right)\hat{\mathbf{H}}^{-1}\ \mathbf{0}\right]\mathbf{E} \tag{11}$$

Furthermore, the matrix gain $\mathbf{L}_u$ will obtain the form [11]:

$$\mathbf{L}_u = \left[\left(\tilde{\mathbf{R}}_N + \mathbf{B}_N^T\mathbf{P}\mathbf{B}_N\right)^{-1}\left(\tilde{\mathbf{G}}_N^T + \mathbf{B}_N^T\mathbf{P}\boldsymbol{\Phi}\right)\hat{\mathbf{H}}_1^{-1}\ \mathbf{0}\right]\mathbf{ED}\,, \tag{12}$$

where **Φ**=exp(**A**T$_o$) and **P** is the symmetric positive-definite solution of the discrete algebraic Riccati equation [1,5].
Note that, in this case, another solution for the matrix pair (**K**, $\mathbf{L}_u$) is given, by:

$$\mathbf{K} = \left(\tilde{\mathbf{R}}_N + \mathbf{B}_N^T\mathbf{P}\mathbf{B}_N\right)^{-1}\left(\tilde{\mathbf{G}}_N^T + \mathbf{B}_N^T\mathbf{P}\boldsymbol{\Phi}\right)\mathbf{H}^1\,, \tag{13}$$

$$\mathbf{L}_u = \left(\tilde{\mathbf{R}}_N + \mathbf{B}_N^T\mathbf{P}\mathbf{B}_n\right)^{-1}\left(\tilde{\mathbf{G}}_N^T + \mathbf{B}_N^T\mathbf{P}\boldsymbol{\Phi}\right)\mathbf{H}^{-1}\mathbf{D} \tag{14}$$

Where $\mathbf{H}^1$ is the left pseudoinverse of matrix **H**, that is, the matrix fulfilling the condition $\mathbf{H}^1\mathbf{H} = \mathbf{I}$.
The resulting discrete closed-loop system matrix $(\mathbf{A}_{cl/d})$ takes the following form:

$\mathbf{A}_{cl/d} = \mathbf{A}_{ol/d} - \mathbf{B}_N\mathbf{KH}$, where cl=closed-loop, ol=open-loop and d =discrete.

## IV. DESIGN AND SIMULATIONS OF RESULTING DISCRETE CLOSED-LOOP POWER SYSTEM MODEL

The power system under study fig 2 [14,15], consists of a 160 MVA turbogenerator with constant excitation voltage $E_{FD}$, supplying power via a step-up transformer and a high-voltage transmission line to an infinite grid. The numerical values of the parameters, which define the open-loop system, as well as its actual operating point, are to be found in Appendix A.

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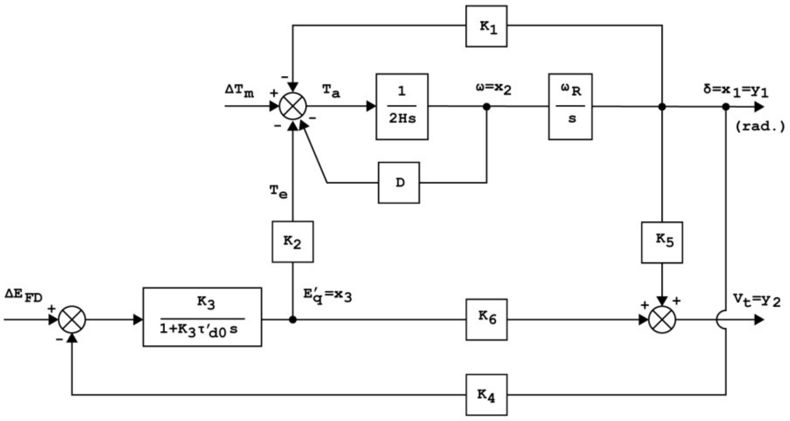


Fig. 2 Simplified representation of investigated practical power system.

Based on the state variables presented in fig. 2 and the values of the parameters and the operating point (see Appendix A), the system of fig. 2 can be described in a state-space form, as in the form of system 1, where:

$\mathbf{x}=\left[\delta \quad \omega \quad E_q'\right]^T, \quad \mathbf{u}=\left[\Delta T_m \quad \Delta E_{FD}\right]^T, \quad \mathbf{y}=\left[\delta \quad v_t\right]^T$

The numerical values of the matrices **A**, **B** and **C** are given in Appendix A.

The eigenvalues of the original continuous open-loop power system models and the simulated responses of the output variables ($\delta$, $\omega$, $v_t$), are presented in Table I and fig. 3, respectively.

Table I. Eigenvalues of original continuous open-loop power system models.

| | | |
|---|---|---|
| Original open-loop power system model | λ | -0.2723+6.2253i<br>-0.2723-6.2253i<br>-0.1889 |

The associated computed discrete linear open-loop power system model, based on the above transformed linearized continuous open-loop system model, is given in Appendix B. The fundamental sampling period $T_o$ is selected for the two cases as:

**case a)** $T_o$ =3.5 sec. and **case b)** $T_o$=7 sec.

The computed magnitude of the eigenvalues of the discrete open-loop power system models and the simulated responses of the output variables ($\delta$, $v_t$), (for both the above two cases), are shown in Table II and fig. 3, respectively.

Table II. Magnitude of eigenvalues of discrete original open-loop and designed closed-loop power system models.

| | | | | | | |
|---|---|---|---|---|---|---|
| Original open-loop power system model | $\lvert\lambda\rvert$ | with | $T_o$=3.5sec. | 0.9731 | 0.9731 | 0.9813 |
| | | | $T_o$=7sec. | 0.9470 | 0.9470 | 0.9629 |
| Designed closed-loop power system model | $\lvert\hat{\lambda}\rvert$ | with | $T_o$=3.5sec. | 0.3600 | 0.1563 | 0.1563 |
| | | | $T_o$=7sec. | 0.2906 | 0.2906 | 0.0333 |

By comparing the eigenvalues of the designed closed-loop power system models to those of the original open-loop power system model the resulting enhancement in dynamic system stability is judged as being remarkable.

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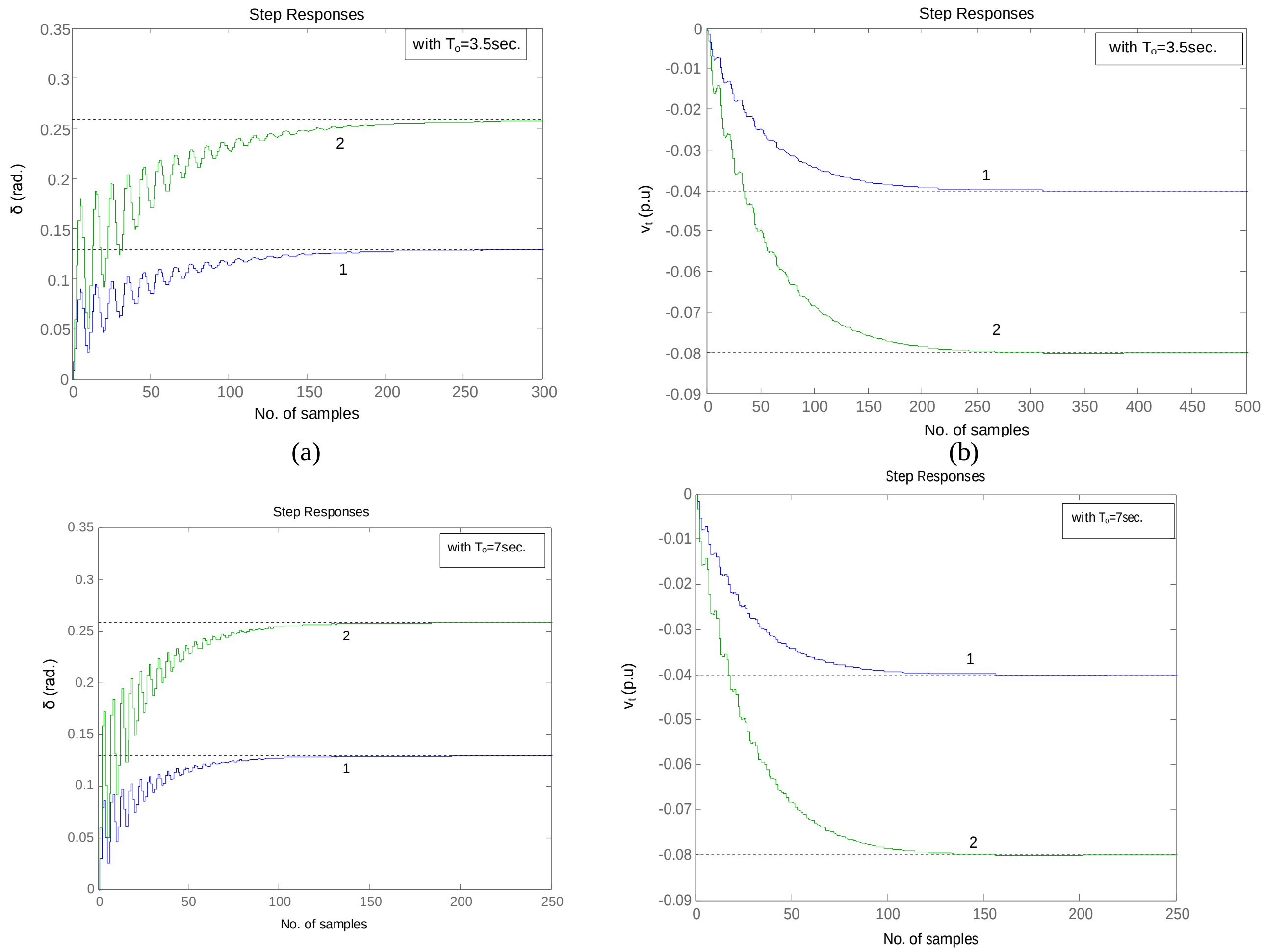


Fig. 3 (a), (b), (c), (d): Simulation results represent the responses ($\delta$, $v_t$) of the discrete response system: (1), (2): for the open loop to step input power load charges $\Delta T_m$=0.05p.u. ($\Delta E_{FD}$=0.0p.u.) and $\Delta T_m$ = 0.10p.u. ($\Delta E_{FD}$=0.0p.u.) respectively.

In the present simulation, our control objective is to solve the problem of minimizing the performance index Eq. 6, using the selected weighing matrices (for the above two cases):
q=3.5 and r=1.
The **K and L$_u$** feedback matrices were computed as:
**for case a):**

$$\mathbf{K} = \begin{bmatrix} 1.2633 & 1.5695 & 1.5 \\ -1.0139 & -0.5481 & 0.0622 \\ 1.9469 & 1.7262 & 1.7556 \end{bmatrix}, \; \mathbf{L}_u = \begin{bmatrix} 0.5081 & -0.0581 & -0.1408 \\ -0.1272 & 0.4092 & -0.0040 \\ -0.4589 & 0.1898 & 0.0878 \end{bmatrix}$$

**and for case b):**

$$\mathbf{K} = \begin{bmatrix} 0.4652 & 0.1886 & -0.1108 \\ 0.0696 & 0.3163 & 0.0643 \\ 0.0918 & 0.3285 & 0.6437 \end{bmatrix}, \; \mathbf{L}_u = \begin{bmatrix} -0.1035 & -0.3467 & 0.0704 \\ 0.1688 & -0.2406 & 0.0089 \\ -0.0043 & 0.5300 & -0.2652 \end{bmatrix}$$

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We select (for both two cases a) and b)) the input and the output multiplicities of the sampling, such as: M = N =5. Finally the nominal parameter vector **θ** has the form [10,12]:

**for case a):** $\boldsymbol{\theta} = [-2.5625 \quad 2.4986 \quad -0.9293 \quad 0.1649 \quad 0.0078 \quad -0.1550]^T$ and

**for case b):** $\boldsymbol{\theta} = [-1.5690 \quad 1.4804 \quad -0.8636 \quad 0.5953 \quad 0.0523 \quad -0.5242]^T$

The numerical values of the matrices referring to the discrete closed-loop power system models of the above two cases are not included here, due to space limitations.

The simulation results for the discrete open-loop power system models and for the closed-loop power system models (i.e.: eigenvalues, eigenvectors, Riccati solutions, responses of system variables etc.), for zero initial conditions and with input disturbances ($\Delta T_m$=0.05 & $\Delta T_m$=0.10), were obtained using special software, based on the theory of §( I,II) and implemented as a typical m-file, running in a MATLAB® environment.

The responses of the output variables (δ, $v_t$) of the designed closed-loop power system models, for zero initial conditions and unit step input disturbance, are shown in fig. 4.

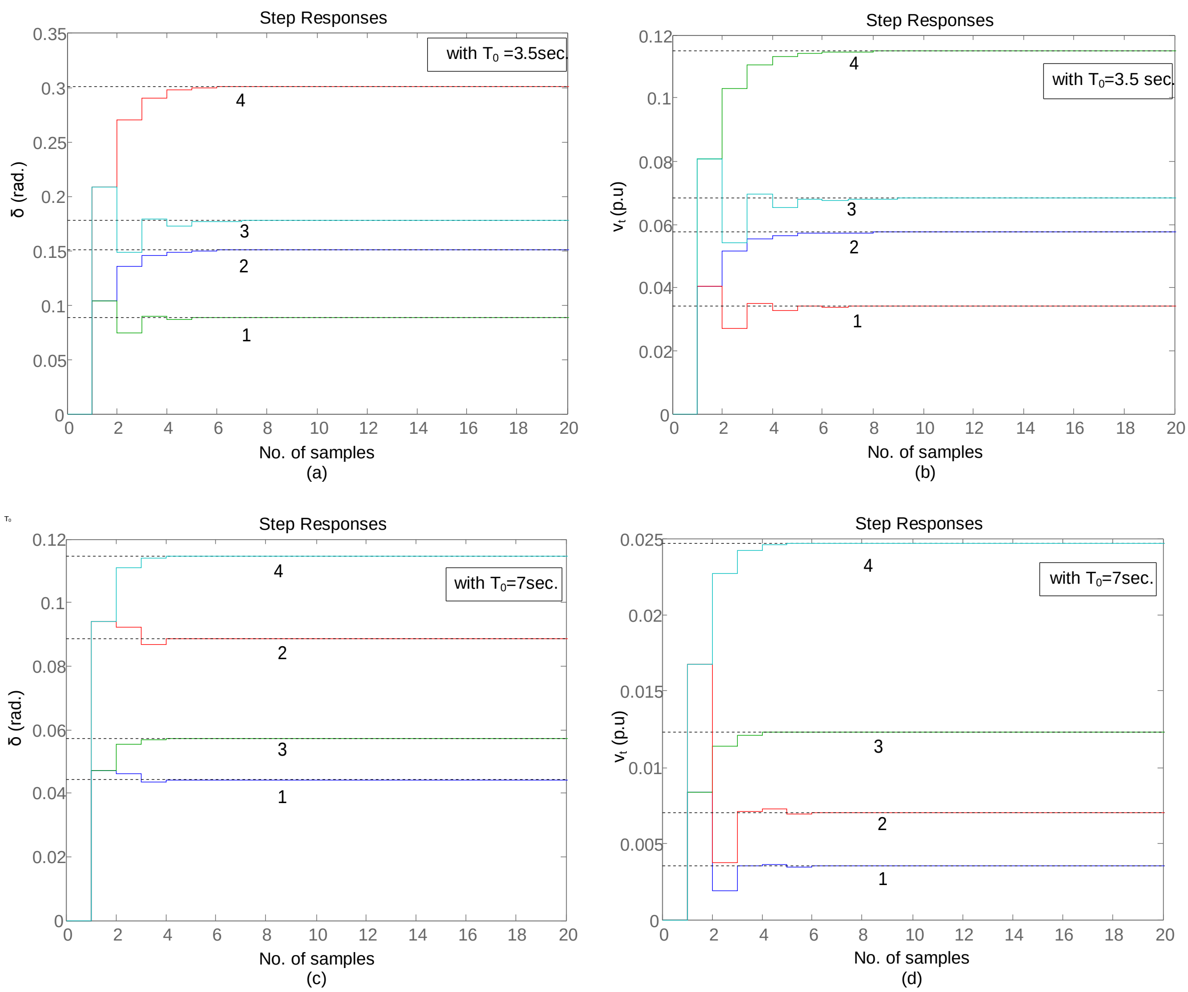


Fig. 4 (a), (b), (c), (d): simulation results represent the responses of the discrete closed-loop models: (1), (2): for the two closed-loop, to step input power load changes $\Delta T_m$=0.05 p.u. ($\Delta E_{FD}$=0.0 p.u.) and ΔTm=0.10 p.u. ($\Delta E_{FD}$=0.0 p.u.) respectively, (3), (4): for the two closed-loop to step input power load changes $\Delta T_m$=0.05 p.u. ($\Delta T_m$=0.0 p.u.) and $\Delta T_m$=0.10 p.u. ($\Delta T_m$=0.0 p.u.) respectively.

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From fig. 4 it is clear that the dynamic stability characteristics of the designed discrete closed-loops models are far more superior than the ones of the original open-loop model, which further attests in favor of the proposed adaptive LQ-TPMRCs-control technique.

## V. CONCLUSION

An efficient control strategy based on two-point multirate controllers has been presented in order to solve the continuous adaptive LQ regulation problem for linear systems and in order to design a desirable excitation controller for an hydrogenerator system, so to enhance its dynamic stability characteristics. The proposed adaptive control scheme offers acceptable closed-loop response as well as more design flexibility, particularly in the cases where the system states are not measurable and system's performance is at least comparable to known LQ optimal regulation methods. The clear simplicity of the TPMRCs used, makes them an appropriate and reliable tool for the design of such implementable controllers.

## REFERENCES

[1] Ogata, K. "Discrete time control systems", Englewood Cliffs, N. J: Prentice-Hall, 1987.
[2] Hagiwara T., Araki M., "Design of a stable state feedback controller based on the multirate sampling of the plant output", IEEE Transactions. Autom. Control, AC-33, pp.812-819, 1988.
[3] Er M.-J., Anderson B.D.O., "Practical issues in multirate-output controllers", Int. J. Control, vol. 53, No. 5, pp.1005-1020, 1991.
[4] Al-Rahmani H.M., Franklin G.F, "A new optimal multirate control of linear periodic and time-invariant system", IEEE Transactions, Autom. Control AC-35, 406–415, 1990.
[5] Sun J., Ioannou P., "Robust adaptive LQ control schemes", IEEE Transactions, Autom. Control AC-37, pp.100–106, 1992.
[6] Tsao T., Hutchinson S., "Multi-rate Analysis and Design of Visual Feedback Digital Servo-Control", Journal of Dynamic Systems Measurement and Control, vol. 116, no. 1, pp. 45-55, 1994
[7] Janardhanan S., Bandyopadhyay B., "Multirate Output Feedback Based Robust Quasi-Sliding Mode Control of Discrete-Time Systems", IEEE Transactions on Automatic Control, vol. 52, No. 3, pp.499-503, 2007.
[8] Narendra K. S., Annaswamy A.M., "Stable Adaptive Systems", Englewood Cliffs, NJ: Prentice Hall, 1989: Dover Publications 2004.
[9] Tao G., "Adaptive Control Design and Analysis", Hoboken, NJ: Wiley-Interscience, 2003.
[10] Arvanitis K. G., "An Indirect Model Reference Adaptive Control Algorithm Based on Multidetected-Output Controllers", Appl. Math. And Comp. Sci., vol. 6, No. 4, pp.667-706, 1996.
[11] Arvanitis K. G., "A New Adaptive Optimal LQ Regulator for Linear Systems Based on Two-Point-Multirate Controllers", Control and Intelligent Systems, vol. 28, No. 1, pp.1-18, 2000.
[12] Arvanitis K .G.,"A New Multirate LQ Optimal Regulator for Linear Time-Invariant Systems and its Stability Robustness Properties", International Journal of Applied Mathematics and Computer Science, vol. 8, pp.101-156, 1998.
[13] Hassan S., Li H., Kamal T., Arifoğlu U., Mumtaz S., Khan L., "Neuro-Fuzzy Wavelet Based Adaptive MPPT Algorithm for Photovoltaic Systems", Energies, vol. 10, no. 3, pp.394, 2017.
[14] Papadopoulos D.P., Boglou A.K., "Turbogenerator-System Controller design via exact model-following techniques", INT. J. Systems Sci., vol. 18, No. 12, pp. 2239-2247, 1987.
[15] Smith J. R., Papadopoulos D.P., Cudworth C. J., Penman J., "Prediction of Forces on the Retaining Structure of hydrogenerator During Severe Disturbance Conditions", Electric Power Systems Research, vol. 14, pp.1-9, 1988.

### Appendix A

Numerical values *of the system parameters and the operating point (p.u. values on generator ratings).*

| | |
|---|---|
| *Turbogenerator:*<br>*160 MVA, 2-pole, pf= 0.894,* $x_q=1.7$, $x_q=1.6$, $x'_d=0.245$*p.u.* $\tau'_{d0}=5.9$, $H=5.5s$; $\omega_R=377rad/s$ $D=2,0$*p.u.* | *Operating point:*<br>$P_0=1.0$, $Q_0=0.5$, $E_{FDo}=2.5128$, $E_{qo}=0.9986$, $V_{t0}=1.0$, $T_{mo}=1.0$*p.u.;* $\delta_0=1,1966rad$; $K_1=1,1330$, $K_2=1.3295$, $K_3=0.3072$, $K_4=1.8235$, $K_5=-0,0433$, $K_6=0.4777$. |
| *External system:*<br>$R_e=0.02$, $X_e=0.40$*p.u. (on a 160 MVA base).* | |

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**Appendix B**

Numerical values of matrices **A**, **B**, **C**, of the original continuous 3[th] –order system:

$$\mathbf{A}=\begin{bmatrix}0 & 377 & 0\\ -0.1030 & -0.1818 & -0.1209\\ -0.3091 & 0 & -5.5517\end{bmatrix},\ \mathbf{B}=\begin{bmatrix}0 & 0\\ 0.0909 & 0\\ 0 & 0.1695\end{bmatrix},\ \mathbf{C}=\begin{bmatrix}1 & 0 & 0\\ -0.0433 & 0 & 0.4777\end{bmatrix}$$

**Appendix C**

Constant matrices of discrete open-loop power system model, based on figs. 1 and 2 with:

**a) sampling period $T_o$ = 3.5 sec.**

$$\mathbf{A}_{ol/d}=\begin{bmatrix}0.8154 & 35.0092 & -0.2153\\ -0.0094 & 0.7985 & -0.0109\\ -0.0282 & 0.5505 & 0.9486\end{bmatrix},\ \mathbf{B}_{ol/d}=\begin{bmatrix}0.1649\\ 0.0084\\ -0.0017\end{bmatrix},\ \mathbf{C}_{ol/d}=\mathbf{C}.$$

$$\mathbf{A}_{cl/d}=\begin{bmatrix}-0.8281 & -1.0242 & -0.8777\\ 2.1548 & 2.3675 & 1.9064\\ -1.2109 & -1.2098 & -0.8826\end{bmatrix},\ \mathbf{B}_{cl/d}=\begin{bmatrix}2.0865 & 0 & 0\\ -3.8912 & 0.9189 & 0\\ 1.8755 & -0.9712 & 0.1432\end{bmatrix},\ \mathbf{C}_{cl/d}=\mathbf{C}.$$

**b) sampling period $T_o$ = 7 sec.**

$$\mathbf{A}_{ol/d}=\begin{bmatrix}0.3422 & 56.6199 & -0.7618\\ -0.0148 & 0.3149 & -0.0170\\ -0.0445 & -1.9477 & 0.9118\end{bmatrix},\ \mathbf{B}_{ol/d}=\begin{bmatrix}0.5953\\ 0.0137\\ -0.0126\end{bmatrix},\ \mathbf{C}_{ol/d}=\mathbf{C}.$$

$$\mathbf{A}_{cl/d}=\begin{bmatrix}-0.1564 & -0.0570 & 0.1638\\ 0.2484 & -0.0871 & -0.1673\\ -0.0162 & 0.2456 & -0.0134\end{bmatrix},\ \mathbf{B}_{cl/d}=\begin{bmatrix}0.9411 & 0 & 0\\ -1.0240 & 1.1229 & 0\\ 0.4352 & -1.3529 & 0.5154\end{bmatrix}.\ \mathbf{C}_{cl/d}=\mathbf{C}.$$