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Research Paper

Excitation Controller Design of a Synchronous Machine Based On Multirate Sampling

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ABSTRACT: *In this paper an H^{∞} -control technique is presented and applied to the design of optimal multirate-output controllers. The technique is based on multirate-output controllers (MROCs) having a multirate sampling mechanism with different sampling period in each measured output of the system. It relies mainly on the reduction , under appropriate conditions, of the original H^{∞} -disturbance attenuation problem to an associated discrete H^{∞} -control problem for which a fictitious static state feedback controller is to be designed, even though some state variables are not available (measurable) for feedback purposes. The proposed H^{∞}-control technique is applied to the discrete linear open-loop system model which represents a 160 MVA synchronous machine with automatic excitation control system , in order to design a proper optimal multirate excitation controller for this power system.*

KEYWORDS: *Disturbance, digital multirate control, H^{∞} -control, power system.*

I. INTRODUCTION

The H^{∞} -optimization control problem has drawn great attention [1-6]. In particular, the H^{∞} -control problem for discrete-time and sampled-data singlerate and multirate systems has been treated successfully [3-6]. Generally speaking, when the state vector is not available for feedback, the H^{∞} -control problem is usually solved in both the continuous and discrete-time cases using dynamic measurement feedback approach.

Recently, a new technique [7] is presented for the solution of the H^{∞} -disturbance attenuation problem. This technique is based on multirate-output controllers (MROCs) and in order to solve the sampled-data H^{∞} -disturbance attenuation problem relies mainly on the reduction, under appropriate conditions, of the original H^{∞} -disturbance attenuation problem, to an associated discrete H^{∞} -control problem for which a fictitious static state feedback controller is to be designed, even though some state variables are not available for feedback.

In the present work the ultimately investigated discrete linear open-loop power system model was obtained through a systematic procedure using a linearized continuous, with impulse disturbances, 9^{th}-order MIMO open-loop model representing a practical power system (which consists of a 160 MVA synchronous machine supplying power to an infinite grid through a proper connection network [8,9]. The digital controller, which will lead to the associated designed discrete closed-loop power system model displaying enhanced dynamic stability characteristics, is accomplished by applying properly the presented MROCs technique.

II. OVERVIEW OF H^{∞}-CONTROL TECHNIQUE USING MROCs [6,7]

Consider the controllable and observable continuous linear state-space system model of the general form

$$\dot{\mathbf{x}}(t)=\mathbf{A}\mathbf{x}(t)+\mathbf{B}\mathbf{u}(t)+\mathbf{D}\mathbf{q}(t)\,,\ \mathbf{x}(0)=\mathbf{0} \tag{1a}$$

$$\mathbf{y}_m(t)=\mathbf{C}\mathbf{x}(t)+\mathbf{J}_1\mathbf{u}(t)\,,\ \mathbf{y}_c(t)=\mathbf{E}\mathbf{x}(t)+\mathbf{J}_2\mathbf{u}(t) \tag{1b}$$

where: $\mathbf{x}(t)\in\mathbf{R}^n$, $\mathbf{u}(t)\in\mathbf{R}^m$, $\mathbf{q}(t)\in\mathbf{L}_2^d$, $\mathbf{y}_m(t)\in\mathbf{R}^{p_1}$, $\mathbf{y}_c(t)\in\mathbf{R}^{p_2}$ are the state, input, external disturbance, measured output and controlled output vectors, respectively. In Eqn. 1 all matrices have real elements and appropriate dimensions. Now follows a useful definition.

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Definition. For an observable matrix pair $(\mathbf{A},\mathbf{C})$, with $\mathbf{C}^T = [\mathbf{c}_1^T \quad \mathbf{c}_2^T \quad \cdots \quad \mathbf{c}_{p_1}^T]$ and $\mathbf{c}_i$ with i=1, …,p_1, the *i*th row of the matrix **C**, a collection of p_1 integers $\{n_1, n_2, \cdots, n_{p_1}\}$ is called an *observability index vector* of the pair $(\mathbf{A},\mathbf{C})$, if the following relationships simultaneously hold

$$\sum_{i=1}^{p_1} n_i = n \ , \ \mathrm{rank}\left[\mathbf{c}_1^T \quad \cdots \quad (\mathbf{A}^T)^{n_1-1}\mathbf{c}_1^T \quad \cdots \quad \mathbf{c}_{p_1}^T \quad \cdots \quad (\mathbf{A}^T)^{n_{p_1}-1}\mathbf{c}_{p_1}^T\right] = n$$

Next the multirate sampling mechanism, depicted in Fig. 1, is applied to Equation 1.

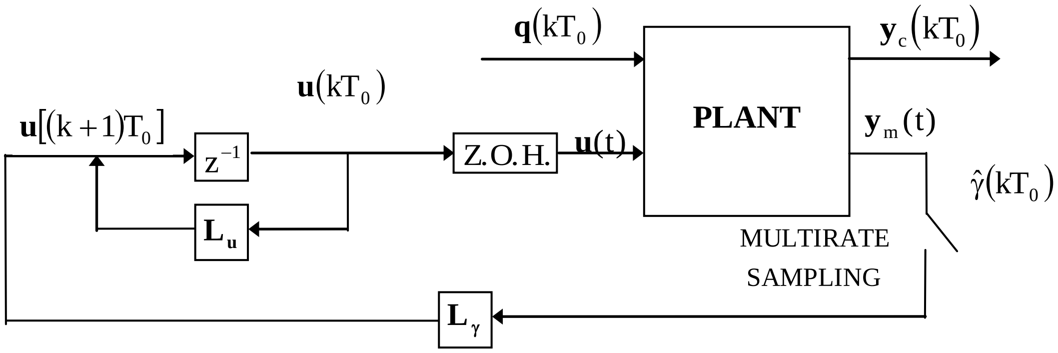


Figure 1. Control of linear systems using MROCs

Assuming that all samplers start simultaneously at t = 0, a sampler and a zero-order hold with period T_0 is connected to each plant input $u_i(t)$, i=1,2,…,m, such that

$$\mathbf{u}(t)=\mathbf{u}(kT_0), \ t \in [kT_0, (k+1)T_0) \tag{2}$$

while the ith disturbance $q_i(t)$, i=1,…,d, and the ith controlled output $y_{c,i}(t)$, i=1,…, p_2, are detected at time kT_0, such that for $t \in [kT_0, (k+1)T_0)$

$$\mathbf{q}(t)=\mathbf{q}(kT_0), \ \mathbf{y}_c(kT_0) = \mathbf{Ex}(kT_0)+\mathbf{J}_2(kT_0) \tag{3}$$

The ith measured output $y_{m,i}(t)$, i=1,…,p_1, is detected at every T_i period, such that for $\mu = 0,..., N_i - 1$

$$y_{m,i}(kT_0 + \mu T_i) = \mathbf{c}_i\mathbf{x}(kT_0 + \mu T_i) + (\mathbf{J}_1)_i\,\mathbf{u}(kT_0) \tag{4}$$

where $(\mathbf{J}_2)_i$ is the ith row of the matrix $\mathbf{J}_2$. Here $N_i \in \mathbf{Z}^+$ are the output multiplicities of the sampling and $T_i \in \mathbf{R}^+$ are the output sampling periods having rational ratio, i.e. $T_i = T_0 / N_i$ with i=1,…, p_1.

The sampled values of the plant measured outputs obtained over $[kT_0, (k+1)T_0)$ are stored in the N^*-dimensional column vector given by

$$\hat{\gamma}(kT_0) = \big[y_{m,1}(kT_0) \quad \cdots \quad y_{m,1}(kT_0 + (N_1 - 1)T_1)$$
$$\cdots \quad y_{m,p_1}(kT_0) \quad \cdots \quad y_{m,p_1}[kT_0 + (N_{p_1} - 1)T_{p_1}]\big]^T \tag{5}$$

(where $N^* = \sum_{i=1}^{p_1} N_i$), that is used in the MROC of the form

$$\mathbf{u}[(k+1)T_0] = \mathbf{L_u}\mathbf{u}(kT_0) - \mathbf{L}_\gamma\hat{\gamma}(kT_0) \tag{6}$$

where $\mathbf{L}_u \in \mathbf{R}^{mxm}, \ \mathbf{L}_\gamma \in \mathbf{R}^{mxN^*}$.

The H^∞-disturbance attenuation problem treated in this paper, is as follows: Find a MROC of the form (2), which when applied to system (1), asymptotically stabilizes the closed-loop system and simultaneously achieves the following design requirement

$$\left\|\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)\right\|_\infty \le \gamma \tag{7}$$

for a given $\gamma \in \mathbf{R}^+$, where $\left\|\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)\right\|_\infty$ is the H^∞-norm of the proper stable discrete transfer function $\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)$, from sampled-data external disturbances $\mathbf{q}(kT_0) \in \ell_2^d$ to sampled-data controlled outputs $\mathbf{y}_c(kT_0)$, defined by

$$\left\|\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)\right\|_\infty = \sup_{\mathbf{q}(kT_0)\in l_2} \frac{\left\|\mathbf{y}_c(kT_0)\right\|_2}{\left\|\mathbf{q}(kT_0)\right\|_2} = \sup_{\theta\in[0,2\pi]} \sigma_{max}\left[\mathbf{T}_{\mathbf{q}\mathbf{y}_c}\left(e^{j\theta}\right)\right] = \sup_{|z|=1} \sigma_{max}\left[\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)\right]$$

where, $\sigma_{max}\left[\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)\right]$ is the maximum singular value of $\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)$, and where use was made of the standard definition of the ℓ_2-norm of a discrete signal $\mathbf{s}(kT_0)$

$$\left\|\mathbf{s}(kT_0)\right\|_2^2 = \sum_{k=0}^{\infty} \mathbf{s}^T(kT_0)\mathbf{s}(kT_0)$$

Our attention will now be focused on the solution of the above H^∞-control problem. To this end, the following assumptions on system (1) are made:

Assumptions:

a) The matrix triplets $(\mathbf{A},\mathbf{B},\mathbf{C})$ and $(\mathbf{A},\mathbf{D},\mathbf{E})$ are stabilizable and detectable.

b) $\operatorname{rank}\begin{bmatrix}\mathbf{A} & \mathbf{D}\\ \mathbf{C} & \mathbf{0}_{p_1xd}\end{bmatrix} = n+d, \quad \operatorname{rank}\begin{bmatrix}\mathbf{A} & \mathbf{B} & \mathbf{D}\\ \mathbf{C} & \mathbf{0}_{p_1xm} & \mathbf{0}_{p_1xd}\end{bmatrix} = n+m+d$

c) $\mathbf{J}_2^T[\mathbf{E} \quad \mathbf{J}_2] = [\mathbf{0}_{m\times n} \quad \mathbf{I}_{m\times m}]$

d) There is a sampling period T_0, such that the open-loop discrete-time system model in general form becomes

$$\begin{aligned}\mathbf{x}[(k+1)T_0] &= \mathbf{\Phi x}(kT_0) + \hat{\mathbf{B}}\mathbf{u}(kT_0) + \hat{\mathbf{D}}\mathbf{q}(kT_0)\\ \mathbf{y}_c(kT_0) &= \mathbf{Ex}(kT_0) + \mathbf{J}_2\mathbf{u}(kT_0)\end{aligned} \tag{8}$$

where $\mathbf{\Phi} = \exp(\mathbf{A}T_0)$, $\left(\hat{\mathbf{B}},\hat{\mathbf{D}}\right) = \int_0^{T_0} \exp(\mathbf{A}\lambda)(\mathbf{B},\mathbf{D})d\lambda$

is stabilizable and observable and does not have invariant zeros on the unit circle.

From the above it fellows that the procedure for H^∞-disturbance attenuation using MROCs essentially consists in finding for the control law a fictitious state matrix **F**, which equivalently solves the problem and then, either determining the MROC pair $(\mathbf{L}_\gamma, \mathbf{L}_u)$ or choosing a desired $\mathbf{L}_\mathbf{u}$ and determining the $\mathbf{L}_\gamma$. As it has been shown in [3], matrix **F** takes the form

$$\mathbf{F} = \left(\mathbf{I} + \hat{\mathbf{B}}^T\mathbf{P}\hat{\mathbf{B}}\right)^{-1}\hat{\mathbf{B}}^T\mathbf{P\Phi} \tag{9}$$

where **P** is an appropriate solution of the following Riccati equation

$$\mathbf{P} = \mathbf{E}^T\mathbf{E} + \mathbf{\Phi}^T\mathbf{P\Phi} - \mathbf{\Phi}^T\mathbf{P}\hat{\mathbf{B}}\left(\mathbf{I} + \hat{\mathbf{B}}^T\mathbf{P}\hat{\mathbf{B}}\right)^{-1}\hat{\mathbf{B}}\mathbf{P\Phi} + \mathbf{P}\hat{\mathbf{D}}_\gamma\left(\mathbf{I} + \hat{\mathbf{D}}_\gamma^T\mathbf{P}\hat{\mathbf{D}}_\gamma\right)\hat{\mathbf{D}}_\gamma^T\mathbf{P}\ ,\ \hat{\mathbf{D}}_\gamma = \gamma^{-1}\hat{\mathbf{D}} \tag{10}$$

It is to be noted that $\gamma \in \mathbf{R}^+$, such that $\left\|\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)\right\| \ge \gamma$ where $\left\|\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)\right\|_\infty$ is the H^∞-norm of the proper stable discrete transfer function $\mathbf{T}_{\mathbf{q}\mathbf{y}_c}(z)$, from sampled-data external disturbances $\mathbf{q}(kT_\mathbf{o}) \in \ell_2^\mathbf{d}$ to sampled-data controlled output $\mathbf{y}_\mathbf{c}(kT_0)$.

Once matrix **F** is obtained the MROC matrices $\mathbf{L}_\gamma$ and $\mathbf{L}_\mathbf{u}$ (in the case where $\mathbf{L}_\mathbf{u}$ is free), can be computed according to the following mathematical expressions

$$\begin{aligned}\mathbf{L}_\gamma &= [\mathbf{F} \quad \mathbf{0}_{m\times d}]\tilde{\mathbf{H}} + \mathbf{\Lambda}\left(\mathbf{I}_{N^*\times N^*} - [\mathbf{H} \quad \mathbf{\Theta}_\mathbf{q}]\tilde{\mathbf{H}}\right)\\ \mathbf{L}_\mathbf{u} &= \left\{[\mathbf{F} \quad \mathbf{0}_{m\times d}]\tilde{\mathbf{H}} + \mathbf{\Lambda}\left(\mathbf{I}_{N^*\times N^*} - [\mathbf{H} \quad \mathbf{\Theta}_\mathbf{q}]\tilde{\mathbf{H}}\right)\right\}\mathbf{\Theta}_\mathbf{u}\end{aligned} \tag{11}$$

where $\tilde{\mathbf{H}}[\mathbf{H} \quad \mathbf{\Theta_q}] = \mathbf{I}$ and $\mathbf{\Lambda} \in \mathbf{R}^{\mathbf{mxN^*}}$ is an arbitrary specified matrix. In the case where $\mathbf{L}_{\mathrm{u}} = \mathbf{L}_{\mathrm{u,sp}}$, we have

$$\mathbf{L}_{\gamma} = [\mathbf{F} \quad \mathbf{L}_{\mathbf{u},\mathrm{sp}} \quad \mathbf{0}_{\mathrm{m \times d}}]\hat{\mathbf{H}} + \mathbf{\Sigma}\left(\mathbf{I}_{\mathrm{N^* \times N^*}} - [\mathbf{H} \quad \mathbf{\Theta_u} \quad \mathbf{\Theta_q}]\hat{\mathbf{H}}\right)$$

where $\hat{\mathbf{H}}[\mathbf{H} \quad \mathbf{\Theta_u} \quad \mathbf{\Theta_q}] = \mathbf{I}$ and $\Sigma \in \mathbf{R}^{\mathbf{mxN^*}}$ is arbitrary.

The resulting closed-loop system matrix $(\mathbf{A}_{\mathbf{cl/d}})$ takes the following general form

$$\mathbf{A}_{\mathbf{cl/d}} = \mathbf{A}_{\mathbf{ol/d}} - \mathbf{B}_{\mathbf{ol/d}}\mathbf{F} \tag{12}$$

where **cl** = closed-loop, **ol** = open-loop and **d** = discrete.

III. DESIGN AND SIMULATIONS OF OPEN- AND CLOSED-LOOP MODELS OF THE POWER SYSTEM

The system under investigation is shown in block diagram form in Figure 2, and consists of a three-phase 160 MVA synchronous machine with automatic excitation control system supplying power through a step-up transformer and a high-voltage transmission line to an infinite grid. The numerical values of the parameters, which define the total system as well as its operating point, come from [9] and are given in Appendix A.

Based on the state variables Fig. 2 and the values of the parameters and the operating point (see Appendix A), the system of Fig. 2 may be described in state-space form, in the form of 1, where

$$\mathbf{x} = \begin{bmatrix} E_q^{'} & \omega & \delta & v_1 & v_2 & v_3 & v_4 & v_5 & v_R & E_{fd} \end{bmatrix}^T$$

$$\mathbf{u} = \begin{bmatrix} \Delta E_{\mathrm{Re}\,f} & \Delta T_m \end{bmatrix}^T, \quad \mathbf{q} = \mathbf{u}$$

$$\mathbf{y}_m = [\delta \quad v_t]^T, \quad \mathbf{y}_c = \mathbf{x}$$

$$\mathbf{E} = \mathbf{I}_{10x10}, \quad \mathbf{J}_1 = 0_{2x2}, \quad \mathbf{J}_2 = 0_{10x2}$$

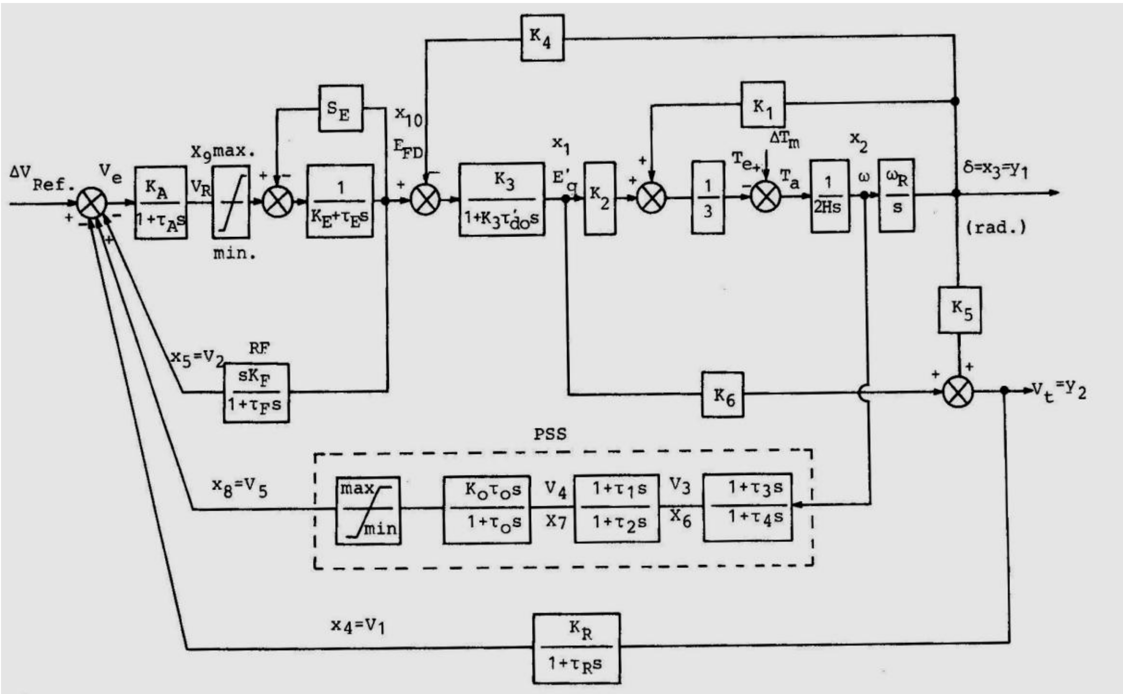


Figure 2. Block diagram representation of regulated synchronous Machine supplying power to an infinite grid.

The computed discrete linear open-loop power system model, based on the associated linearized continuous open-loop system model described in Appendix 2 of [9], is given below in terms of its matrices with sampling period $T_0 = 0.4$ sec.

$$\mathbf{A}_{ol/d}=\begin{bmatrix} 0.6808 & -5.4034 & -0.0745 & -0.0841 & -0.3513 & -0.3905 & -0.2572 & 0.3942 & 0.0018 & 0.0506 \\ -0.0100 & 0.2719 & -0.0096 & 0.0006 & 0.0018 & 0.0020 & 0.0011 & -0.0020 & 0.0 & -0.0004 \\ -0.8058 & 92.9580 & 0.2750 & 0.0224 & 0.0579 & 0.0624 & 0.0299 & -0.0619 & -0.0006 & -0.0185 \\ 0.3770 & -5.8500 & -0.0524 & -0.0362 & -0.1360 & -0.1534 & -0.0926 & 0.1506 & 0.0008 & 0.0225 \\ -0.1734 & 1.0489 & 0.0107 & -0.0245 & 0.3595 & -0.2874 & -0.3251 & 0.3800 & 0.0003 & -0.0122 \\ -0.0141 & -0.6437 & -0.0147 & 0.0014 & 0.0048 & 0.0184 & 0.0031 & -0.0053 & 0.0 & -0.0009 \\ -0.0078 & -2.0973 & -0.0132 & 0.0030 & 0.0120 & -0.1990 & 0.0215 & -0.0134 & -0.0001 & -0.0016 \\ -0.0067 & -2.0913 & -0.0122 & 0.0029 & 0.0119 & -0.1676 & -0.9482 & 0.9475 & -0.0001 & -0.0016 \\ -12.3587 & 122.1028 & 1.4904 & 3.2910 & -14.4844 & 6.4718 & -29.3545 & 24.1441 & -0.0635 & -0.5357 \\ -5.2071 & 30.8392 & 0.3013 & -1.0662 & -9.7173 & -9.3513 & -9.5697 & 11.6895 & 0.0170 & 0.6346 \end{bmatrix}$$

$$\mathbf{B}_{ol/d}=\begin{bmatrix} 0.3995 & -0.0020 & -0.0624 & 0.1524 & 0.3887 & -0.0053 & -0.0136 & -0.0134 & 25.4486 & 11.9382 \\ -0.0480 & 0.0273 & 2.0098 & -0.0856 & 0.0421 & 0.0431 & 0.0428 & 0.0399 & 4.0183 & 1.2487 \end{bmatrix}^T$$

$$\mathbf{C}_{ol/d}=\begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.4777 & 0 & -0.0433 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Based on Fig. 1 the H^{∞}-control using MROCs (given in this paper), the computed discrete linear open-loop model of the power system under study, the discrete closed-loop power system models were designed considering the cases with γ =4.5 and the compted values of **BN**, **K**, **Lu** and **F** feedback gain matrices were computed as

$$\mathbf{BN}=\begin{bmatrix} 1.4306 & 0.1834 & 0.0142 & 0.0003 & -18.5449 & -4.6020 & -0.9837 & -0.1579 & -0.0115 \\ 1.5897 & 1.1686 & 0.5590 & 0.1441 & 7.5561 & 1.3453 & 0.1755 & 0.0060 & -0.0031 \end{bmatrix}^T$$

$$\mathbf{K}=10^3*\begin{bmatrix} 3.2267 & -9.2928 & 9.2945 & -3.2283 & 0.0301 & 0.6151 & -0.3089 & -0.2690 & -0.0676 \\ 2.5053 & -7.2136 & 7.2129 & -2.5048 & 0.0234 & 0.4772 & -0.2414 & -0.1890 & -0.0719 \end{bmatrix}$$

$$\mathbf{F}=\begin{bmatrix} -0.4313 & -0.2491 & 0.0509 & 0.0350 & -0.7510 & -0.2304 & -1.0420 & 1.0037 & -0.0008 & 0.0146 \\ -0.5301 & 33.3453 & 0.0284 & 0.2996 & 0.3983 & 1.4627 & -0.5769 & 0.0544 & -0.0055 & -0.1109 \end{bmatrix}$$

$$\mathbf{L}_u=\begin{bmatrix} 0.61150959 & -0.00000044 \\ -0.09626196 & 0.00000038 \end{bmatrix}$$

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 magnitude of the eigenvalues of the discrete original open-loop and designed closed-loop power system models are shown in Table 1. 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.

Table 1. Magnitude of eigenvalues of discrete original open-loop and Designed closed-loop power system models.

Original open-loop power system model		$\lvert\lambda\rvert$	**0.9087 0.9087 0.6985 0.6985 0.9608 0.4263 0.0211 0.0076 0.0005 0.0005**
Designed closed-loop power system model	**with γ=4.5**	$\lvert\hat{\lambda}\rvert$	**0.7881 0.6999 0.9608 0.4082 0.2500 0.2500 0.0464 0.0068 0.0003 0.0**

The responses of the output variables (v_t and δ) of the original open-loop and designed closed-loop power system models for zero initial conditions and unit step input disturbance are shown in Figs. 3,4,5 respectively.

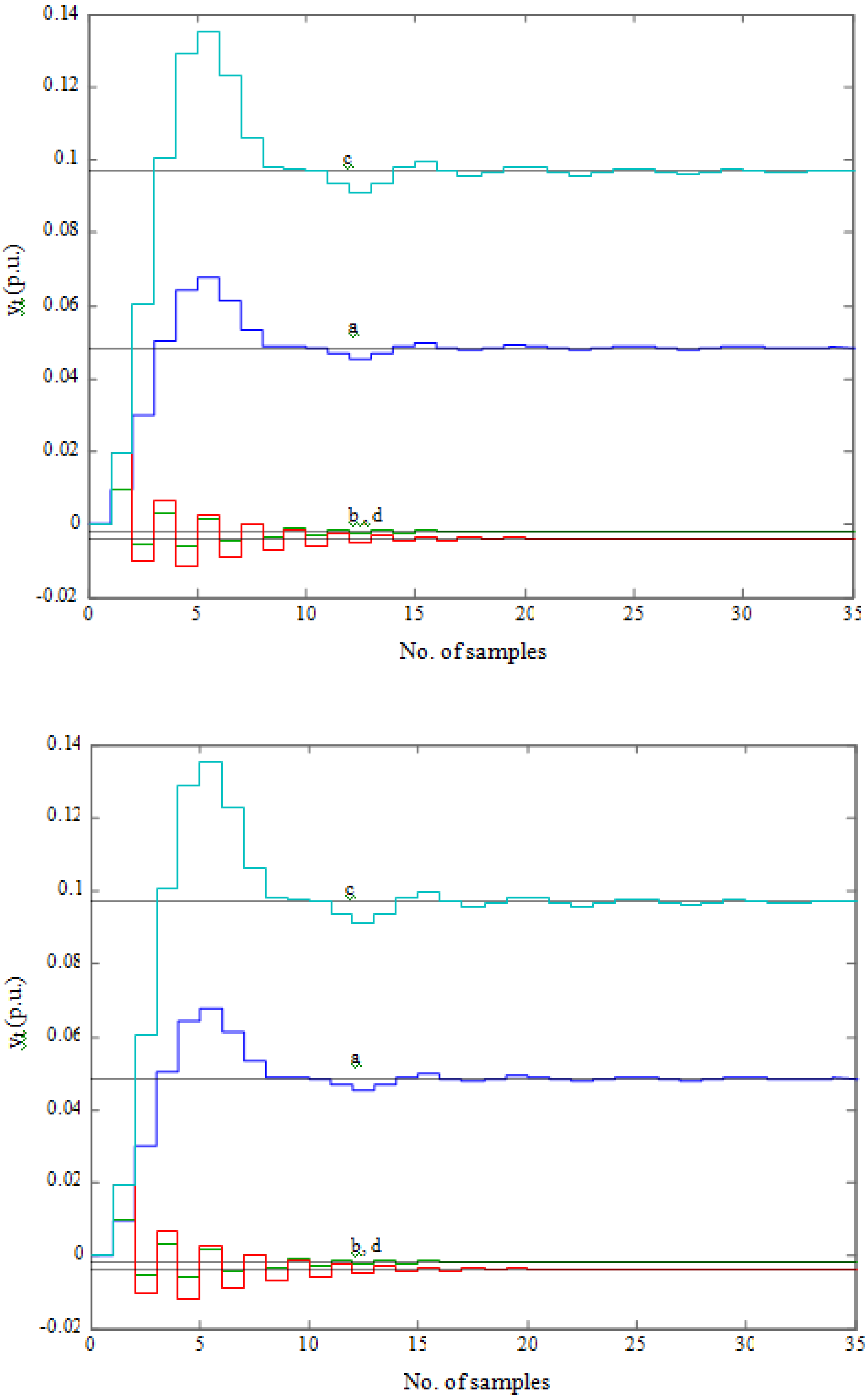


Figure 3. Responses of δ and v_t of the discrete open loop (a), (c) and close loop (b), (d) system to step input changes: (a), (b): ΔV_{ref} =0.05, ΔT_m= 0.0 and (c), (d): ΔV_{ref} =0.10, ΔT_m= 0.0.

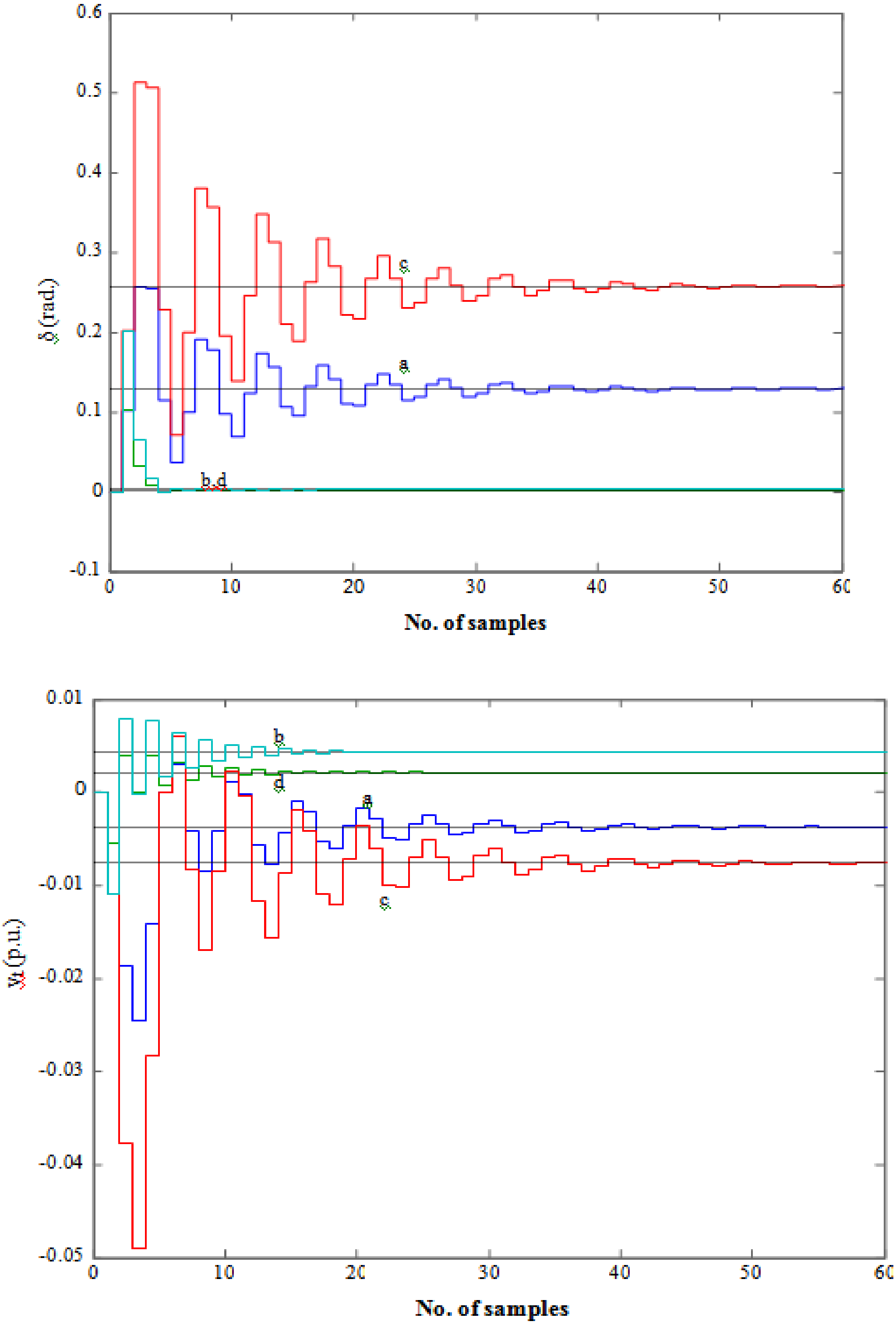
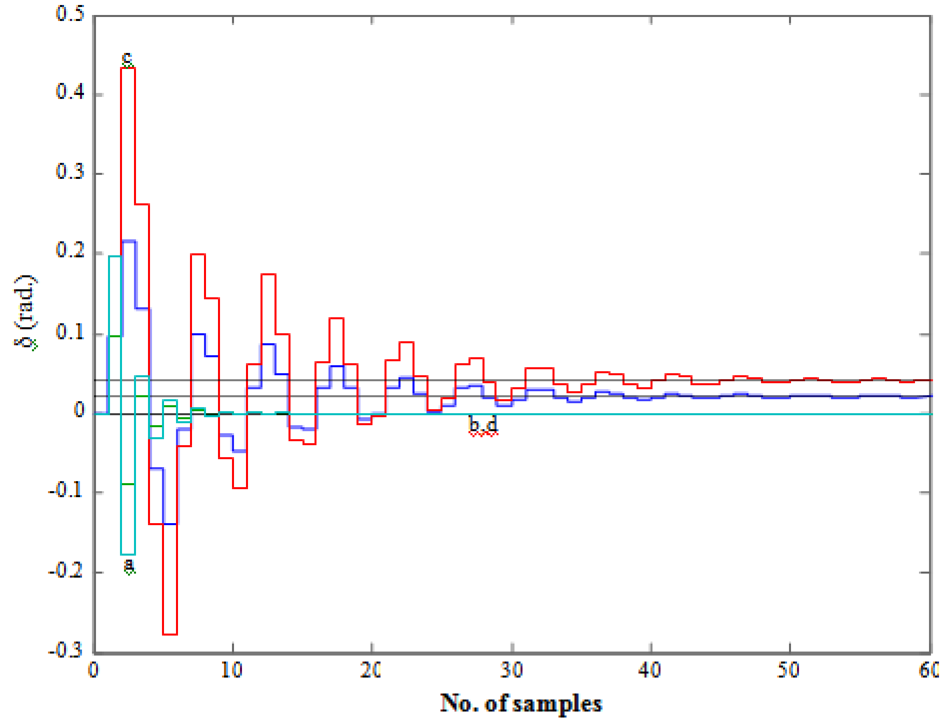


Figure 4. Responses of δ and v_t of the discrete open loop (a), (c) and close loop (b), (d) system to step input changes: (a), (b): ΔV_{ref} =0.0, ΔT_m= 0.05 and (c), (d): ΔV_{ref} =0.0, ΔT_m= 0.10.



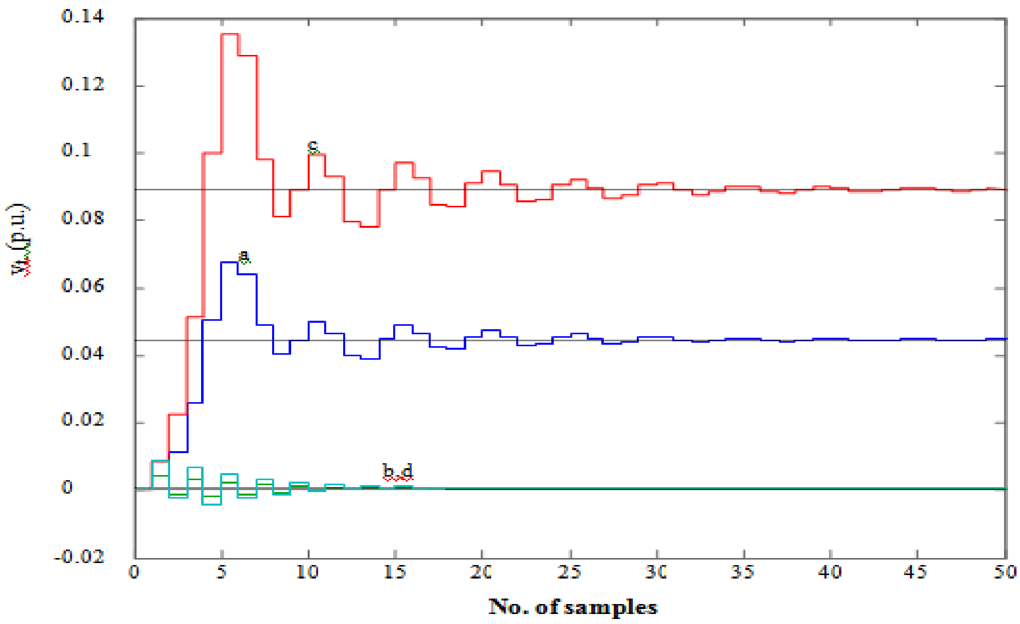


Figure 5. Responses of δ and v_t of the discrete open loop (a), (c) and close loop (b), (d) system to step input changes: (a), (b): ΔV_{ref} =0.05, ΔT_m= 0.05 and (c), (d): ΔV_{ref} =0.10, ΔT_m= 0.10.

From Figs. 3,4,5 it is clear that the dynamic stability characteristics of the designed discrete closed-loop system-models are far more superior than the corresponding ones of the original open-loop model, which attests in favour of the proposed H^{∞}-control technique.

It is to be noted that the solution results of the discrete system models , i.e. eigenvalues, eigenvectors, responses of system variables etc., for zero initial conditions were obtained using a special software program, which is based on the theory of & 2 and runs on MATLAB program environment.

In Fig. 6, the maximum singular value of $T_{qy_C}(z)$ is depicted, as a function of the frequency ω. Clearly, the design requirement $\left\| \mathrm{T}_{qy_c}(z)_{\infty} \right\| \leq 1$, is satisfied. Moreover, as it can be easily checked the poles of the closed

loop system, lie inside the unit circle. Therefore, the requirement for the stability of the closed-loop system is also satisfied.
Not that, the H$^{\infty}$-norm of the open-loop system transfer function between disturbances and controlled outputs has the value $\left\| C(j\omega I - A)^{-1} B \right\|_{\infty} = 79.5687$.

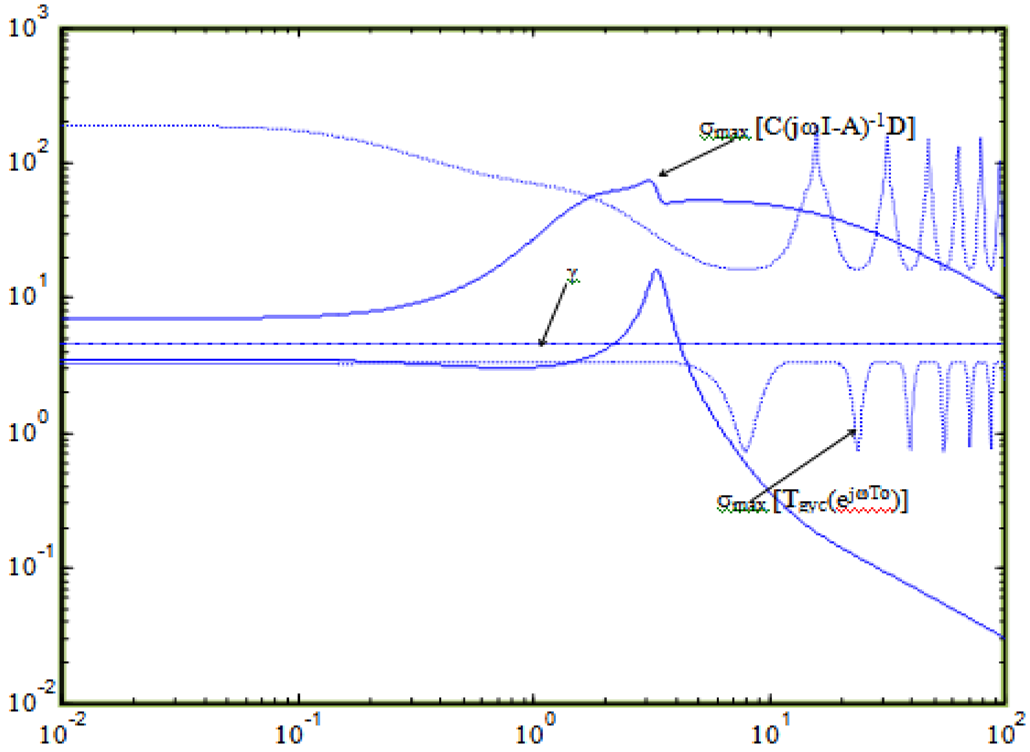


Figure 6. The maximum singular value of $T_{qy_c}(z)$ over ω, for the unsaturated machine and for γ=4.5

IV. CONCLUSIONS

An efficient H$^{\infty}$ -control technique based on MROCs has been presented in concise form for the purpose of attenuating in an effective manner system disturbances which otherwise degrade the performance of a synchronous generator. The method was applied successfully to a discrete open-loop power system model (which was computed from an original continuous linearized open-loop one) resulting in the design of an associated discrete closed-loop power system model. The results of the simulations performed on the discrete open- and closed-loop power system models demonstrated clearly the significant enhancement of the dynamic stability characteristics achieved by the designed closed-loop model. Thus this H$^{\infty}$ -control technique was proved to be a reliable tool for the design of implementable MROCs.

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APPENDIX A

Numerical values of system parameters and operating point

Synchronous machine: 3-phase, 160 MVA, pf=0.094, xd=1.7, xq=1.6, $x_d^{'} = 0.245\,p.u.$; $\tau_{do}^{'} = 5.9$, H=5.4 s; ωR =314 rad. s-1.
Type-1 exciter: KA=50, KE= -0.17, SE = 0.95, KF = 0.04, KR = 1, Ko =1; τA = 0,05, τE = 0,95, τF = 1, τR = 0.05, τo = 10 p.u., τ1 = τ3 = 0.440, τ2 = τ4 =0,092 s.
External system: Re = 0.02, Xe = 0.40 p.u., (on 160 MVA base).
Operating point: Po=1, Qo=0.5, EFDo=2.5128, Eqo=0.9986, vto=1, Tmo=1 p.u.; δo=1.1966 rad.; K1=1.1330, K2=1.3295, K3=0.3072, K4=1.8235, K5=-0.0433, K6=0.4777.

APPENDIX B

Numerical values of matrices A, B and C of the original 10th-order system

$$\mathbf{A} = \begin{bmatrix} -0.5517 & 0 & -0.3091 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1695 \\ -0.0410 & 0 & -0.0350 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 314.1593 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 9.5540 & 0 & -0.8660 & -20 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0.0421 & -0.0328 \\ -0.1962 & 10.8696 & -0.1672 & 0 & 0 & -10.8696 & 0 & 0 & 0 & 0 \\ -0.9386 & 51.9849 & -0.7999 & 0 & 0 & -41.1153 & -10.8696 & 0 & 0 & 0 \\ -0.9386 & 51.9849 & -0.7999 & 0 & 0 & -41.1143 & -10.8696 & -0.1 & 0 & 0 \\ 0 & 0 & 0 & -1000 & -1000 & 0 & 0 & 1000 & -20 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.0526 & -0.8211 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1000 & 0 \\ 0 & 0.0926 & 0 & 0 & 0 & 0.4428 & 2.1179 & 2.1179 & 0 & 0 \end{bmatrix}^T$$

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.4777 & 0 & -0.0433 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$