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H∞ TCSC Controller and Fuzzy PSS Design in Mitigating Small Signal Oscillations

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ABSTRACT

This paper proposes a hybrid controller scheme for enhancement of steady state stability in the presence of uncertainties in power systems. The procedure employs a robust TCSC assisted by a Fuzzy PSS designed with the uncertain model of power system. The resulting controller provides excellent damping of oscillations at low frequencies for a SMIB system. The Simulation results show the great enhancement in the steady state stability of the power system. The proposed controllers combined stabilize the power system with effective damping of low frequency oscillations.

Keywords

FACTS- Flexible AC transmission system, TCSC- Thyristor controlled series capacitor

1. INTRODUCTION

Low frequency (0.1-1.0 Hz) power oscillations [1] are inherent in electric power systems. Traditionally, the additional damping in system is provided by power system stabilizer (PSS) [2-4]. However, with growing transmission line loading, the power system stabilizer (PSS) may not provide enough damping for the inter-area power oscillations in a complex power system. In addition, it may result in large variations in the voltage profile, leading power factor operation and even losing system stability under large disturbances [5–7].

In these days, Power electronic based Flexible AC Transmission Systems (FACTS) controllers are widely recognized [8, 9] by power system practitioners for controlling the power flow along the transmission lines and improving power oscillation damping. One of the promising Series FACTS device, thyristor controlled series capacitor (TCSC) is able [10, 11] to control the power flow, provide damping to the inter-area and local mode oscillations, and improve transient stability.

It is a well known fact that the conventional damping controller design synthesis is simple but tends to lack of robustness even after a lot of tuning. Several research studies have been reported in the literature for tuning damping controller parameters. To design the power system stabilizers [12] a variety of design methods such as frequency response [13], pole placement [14], eigen value sensitivity [15], residue method [16] and robust control techniques have been proposed. To design the TCSC and PSS the most common techniques are based on simulated annealing [17], phase compensation method [18] and genetic algorithm [19].All of these techniques do not take the presence of uncertainties such as variations of loading conditions, system parameters and generating conditions into consideration in the system modelling, the robustness of PSS and TCSC against system uncertainties cannot be guaranteed. Therefore, PSS and TCSC may fail to stabilize the system under varying operating conditions.

In the proposed control scheme a H∞ loop shaping TCSC controller and Fuzzy Power system stabilizer in a Single Machine infinite Bus (SMIB) power system is demonstrated. The simulation studies clearly show that the proposed hybrid controllers are highly robust to different system uncertainties. This paper is organized as follows. First; system modelling is explained in section II, the design of the proposed TCSC and PSS structures are detailed in Section III. Next section IV shows the simulation studies and the effectiveness of TCSC and PSS has been validated on Single Machine infinite Bus (SMIB) power system in different conditions, the conclusion is given in section V.

2. POWER SYSTEM MODELLING

The study power system consists of a synchronous generator connected to an infinite bus through a transmission line. A H∞ TCSC and a fuzzy pss are installed with the system (Fig. 1). In the figure, Re and Xe represent the resistance and the reactance of the transmission line, Vt and V_B are the generator terminal and infinite bus voltages respectively.

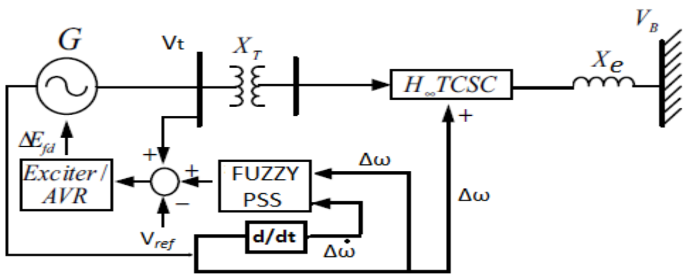

Fig 1: TCSC and Fuzzy PSS installed in a SMIB system

Fig.2 shows the block diagram of Single Machine infinite bus (SMIB) power system. This diagram was developed by Heffron and Phillips [1952] to represent the dynamics of a single synchronous generator connected to the grid through a line. This model is a well-known linear model and is quite accurate for studying low frequency oscillations and stability of power systems. The state space representation for the P-H model in Fig.2 is expressed as:

$$\Delta\dot{X} = A.\Delta X + B.\,\Delta U$$

$$\Delta Y = C.\Delta Y + D.\,\Delta U$$

where the state vector $\Delta X = [\Delta\delta, \Delta\omega, \Delta E_q', \Delta E_{fd}]^T$ and the output

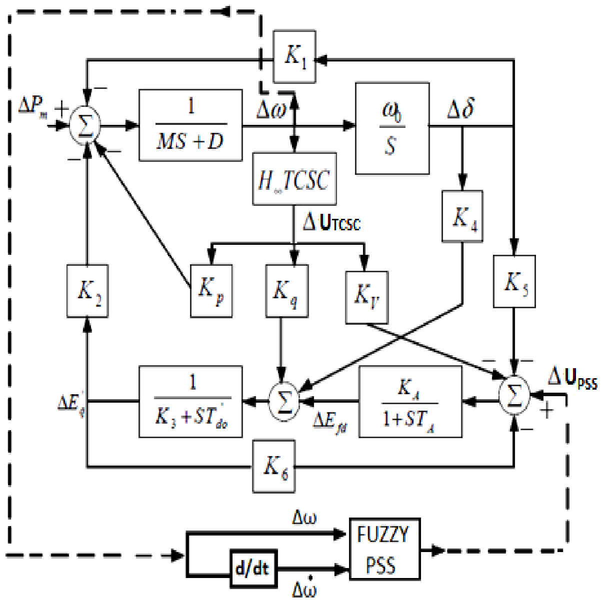

Fig 2: P-H model of SMIB system connected with H_∞TCSC and Fuzzy PSS

vector **$\Delta Y = [\Delta\omega]$. $\Delta U = [\Delta U_{PSS}, \Delta U_{TCSC}]^T$** are the control signals from Fuzzy PSS and Robust TCSC, which uses the angular velocity deviation (Δω) as a feedback input signal.

Table 1. K- constants at different loading conditions

K-Constants	**Loading**		
	(a) Light Loading (P=0.1pu)	**(b) Nominal Loading (P=0.5 pu)**	**(c) Heavy Loading (P=1.0pu)**
K1	**0.8**	**1.80**	**2.2**
K2	**0.6**	**1.70**	**2.35**
K3	**0.19**	**0.19**	**0.19**
K4	**0.70**	**1.75**	**2.25**
K5	**0.30**	**0.06**	**0.025**
K6	**0.29**	**0.27**	**0.24**
K7	**-0.04**	**-0.20**	**-0.38**
K8	**0.15**	**1.00**	**2.30**
K9	**00.4**	**2.10**	**4.30**

Here, the Fuzzy Logic Control and H_∞ loop shaping approaches are applied to design a Fuzzy PSS and Robust TCSC respectively.

The coefficients K_1 ,K_2 ,K_3 K_4 ,K_5 ,K_6 ,K_7 ,K_8 and K_9 as shown in Fig.2 are calculated for three different loading conditions given in Table I for an example power system [11]. The transmission line reactance is considered as 0.4 pu. The Matlab simulations were performed considering the reactance of the TCSC equal to 0.3pu.The above variation of K constants at three different operating points is considered as uncertainty for H_∞ TCSC controller design.

3. FUZZY PSS AND ROBUST TCSC CONTROL DESIGN

3.1 Robust TCSC Loop shaping Control Design using Glover-McFarlane method

The H_∞ TCSC design is based on the classical loop-shaping, where loop-shape refers to the magnitude of the loop transfer function L = *GK* as a function of frequency. The control method for designing Robust TCSC controller uses a combination of loop shaping and robust stabilization as proposed in McFarlane and Glover [20-21].The first step is to select a pre- and post-compensator W_1 and W_2, so that the gain of the shaped plant Gs = W_2GW_1 is sufficiently high at frequencies where good disturbance attenuation is required and is sufficiently low at frequencies where good robust stability is required. The second step is to compute a Glover-McFarlane H_∞ normalized co prime factor loop-shaping controller $K=W_2*Ks*W_1$, where $K_s = K_\infty$ is an optimal H_∞ controller.

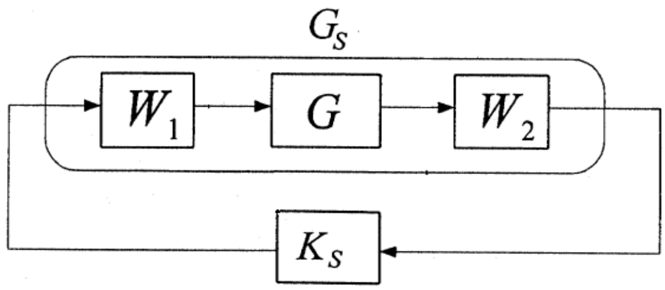

Fig 3: Shaped plant (Gs) with H_∞ controller (Ks)

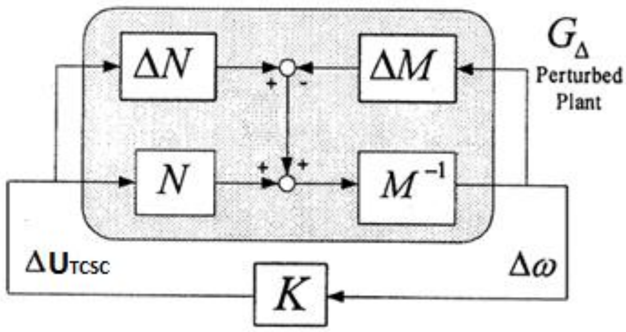

Fig 4: H_∞ Robust Stabilization

A shaped plant G_S, is expressed in the form of normalized left co prime factorization $G_S = M^{-1}N$ then a perturbed plant model G_Δ is defined as

$$G_\Delta = (M+\Delta M)^{-1}(N+\Delta N)$$

where ΔM and ΔN represent the uncertainty in the nominal plant model G. The objective of robust stabilisation is to stabilise a family of perturbed plants defined by:

$$G_\Delta = \{(M+\Delta M)^{-1}(N+\Delta N) : \|\Delta N \; \Delta M\|_\infty < 1/\gamma\} \qquad (1)$$

By the definition in (1) the *H*- robust stabilization problem via NCF approach can be established by G_Δ, and *K* as depicted in Fig. 4. The objective of robust control design is to stabilize the nominal plant G and the family of perturbed plants defined by G_Δ.

In (1), $1/\gamma$ is defined as the robust stability margin. The maximum stability margin $1/\gamma$ in the presence of system uncertainties is given by the lowest achievable value of γ, i.e. γ_{min}. The value of γ_{min}, can be calculated by(2),

$$\gamma_{min} = \sqrt{(1 + \lambda max\,(XZ))} \qquad (2)$$

where $\lambda max\,(XZ)$ denotes the maximum eigen value of XZ . For a minimal state-space realization (A, B, C, D) of G_S, the values of X and Z are the unique positive definite solutions to the algebraic Riccati equations

$$(A-BS^{-1}D^TC)^TX+X\,(A-BS^{-1}D^TC) - XBS^{-1}X+ C^TR^{-1}C=0$$

$$(A-BS^{-1}D^TC)Z+Z\,(A-BS^{-1}D^TC)^T-Z\,C^TR^{-1}CZ+BS^{-1}B^T=0$$

Where $R=I+DD^T$, $S= I+D^TD$.

γ gives a good indication of robustness of stability to a wide class of plant variations. To ensure the robust stability of the nominal plant, the weighting function is selected so that $\gamma_{min} \leq 4.0$ for most typical control system designs [22]. If γ_{min} is not satisfied, then we have to adjust the weighting function. The H_∞ Controller can be determined by

$$K_\infty = \begin{bmatrix} A + BF + \gamma^2 (L^T)^{-1} ZC^T(C+DF) & \gamma 2\,(L^T)^{-1} ZC^T; \\ B^TX & -D^T \end{bmatrix} \qquad (3)$$

Where $F = -S^{-1}(D^T C + B^T X)$ and $L= (1 - \gamma 2)\, I + XZ$

Now, the Robust TCSC controller $K=W_1 {*} K_\infty {*} W_2$ is find out that satisfies the necessary condition-

$$\|[I \;\; K_\infty]^t\,(I - Gs\,K_\infty)^{-1}[\,I \;\; Gs\,]\|_\infty \leq \gamma$$

3.2 Fuzzy PSS Design

Fig. 6 shows the FIS Editor with two input variable blocks, one output variable block and Mamdani FLC [23-27] block. The designing process is carried out with the help of MATLAB.Fuzzy controller Design process involves 3 steps: fuzzification, fuzzy rules and defuzzification.

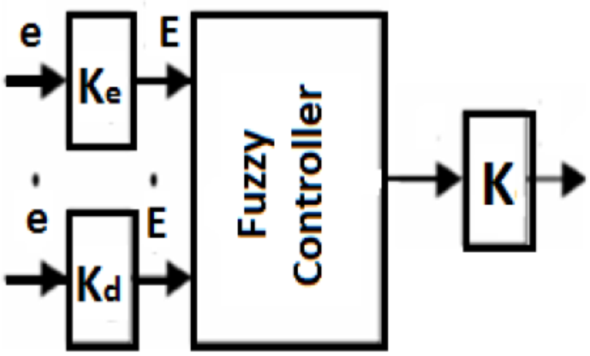

Fig 5: Basic Structure of a Fuzzy Logic Power System Stabilizer

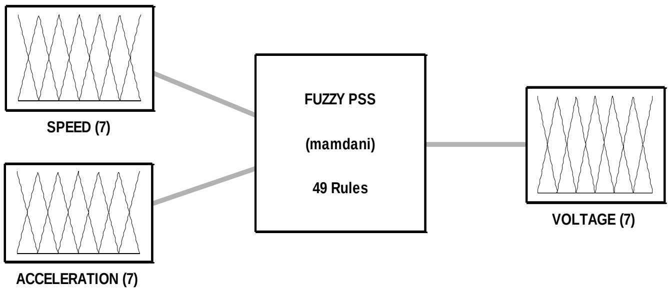

Fig 6: FIS Editor FLC

3.2.1 Fuzzification

Fuzzification process is used for converting speed and its derivative to the fuzzy values. Seven membership functions to generate better results are defined in Table II. The linguistic labels of membership functions are marked as in fig. 7, NB (Negative Big), NM (Negative-Medium), NS (Negative-Small), ZR (Zero), PS (Positive-Small), PM (Positive-Medium), PB (Positive-Big) Membership functions are used to convert the fuzzy values between 0 and 1for inputs and output value both.

3.2.2 Fuzzy Rules

Fuzzy rules are defined to reduce the error in the system after analyzing the function of controller. For each fuzzy value there are

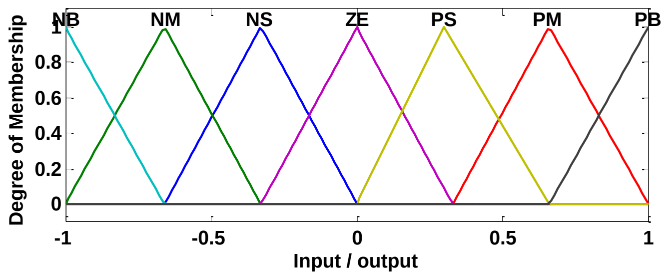

Fig 7: Membership functions for Fuzzy PSS for input and output variables

seven membership functions, so 49 combinations of speed and acceleration are possible. There is an output for each of the

Table 2. Design parameters of Fuzzy PSS

Speed dev. ↓	ACCELERATION						
	NB	NM	NS	ZR	PS	PM	PB
NB	NB	NB	NB	NB	NM	NM	NS
NM	NB	NM	NM	NM	NS	NS	ZR
NS	NB	NM	NM	NM	NS	NS	ZR
ZR	NM	NS	NS	ZR	PS	PS	PM
PS	NS	ZR	ZR	PS	PS	PM	PM
PM	ZR	PS	PS	PM	PM	PM	PB
PB	PS	PM	PM	PB	PB	PB	PB

membership functions and the linguistic label can be determined by using IF–THEN fuzzy rules in the following form: ***If speed deviation is a_i and acceleration deviation is b_j then fuzzy output is c_{ij}.*** Where a_i, b_j and c_{ij} are fuzzy subsets defined in Table 2.

3.2.3 Defuzzification

At last Defuzzification is done. In this step the fuzzy values which are obtained from inference engine converts into the specific values. For the inference Mamdani's minimum fuzzy implication and Max–Min compositional rule are used. For the defuzzification, centroid method is used. At first, we design a parameters satisfying FLC, according to design rules and with assumption given in previous section.

4. SIMULATION STUDIES

To demonstrate the robustness of proposed control design, the single machine infinite Bus (SMIB) power system is simulated. The Weighting functions for H_∞ TCSC controller are appropriately selected as $W_1=(S+1)/0.9S$ and $W_2=I$. Consequently, the shaped plant G_s can be established and the controller K_∞ can be determined by (3). As a result, the robust TCSC controller K_∞ is obtained.

The Power system shown in Fig.1 is studied through the computer simulation using the MATLAB/Simulink in MATLAB environment.

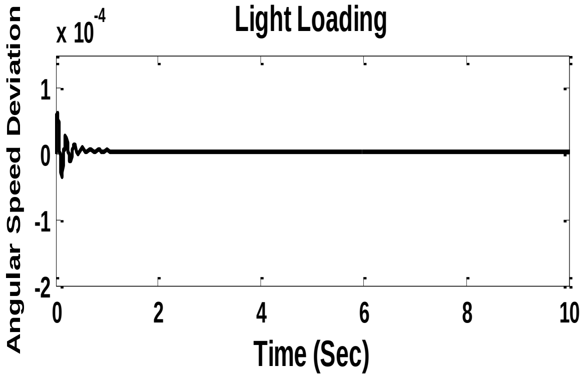

Fig 8 (a): Simulation results of case (a)

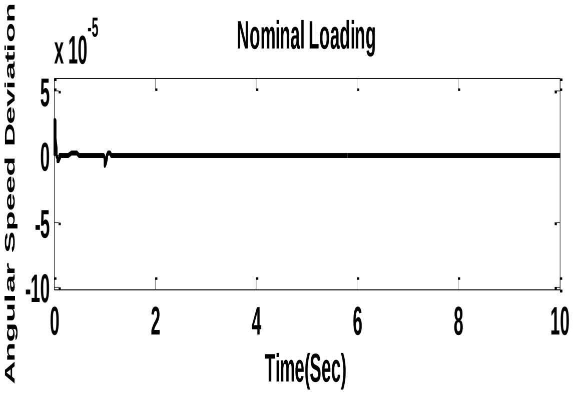

Fig 8 (b): Simulation results of case (b)

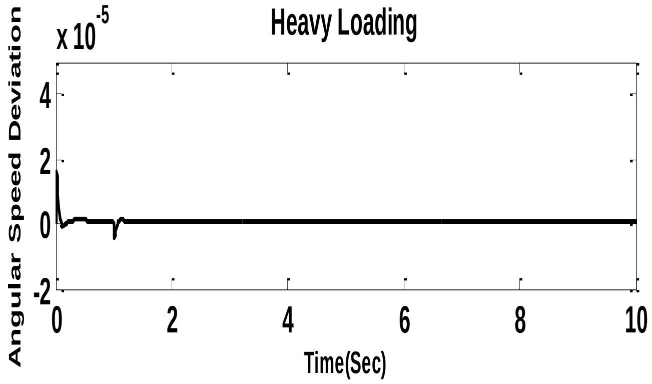

Fig 8 (c): Simulation results of case (c)

Fig 8 (a)-(c): Angular Speed Deviation (Δω) With H_∞ TCSC and Fuzzy PSS

A 30% step deviation in mechanical power input at t =1.0 sec is considered. The performance of the proposed controllers is tested for three different loading conditions and compared with the case without controllers. Fig. 8(a)-(c) and Fig. 9(a)-(c) shows the system response with and without controllers with respect to time for the three cases. The above response clearly shows that in the absence of Fuzzy PSS and TCSC Controller in hybrid control scheme there are substantial oscillations in the system. The system has large oscillations and unstable in nature. In contrast, the proposed H_∞ TCSC & Fuzzy PSS hybrid controllers (Table 3) are able to significantly damp these oscillations. Now, the system has much smaller overshoot (Mp), much smaller settling time (ts) & $e_{ss} = 0$ for speed deviation (Δω) for all the three loading conditions.

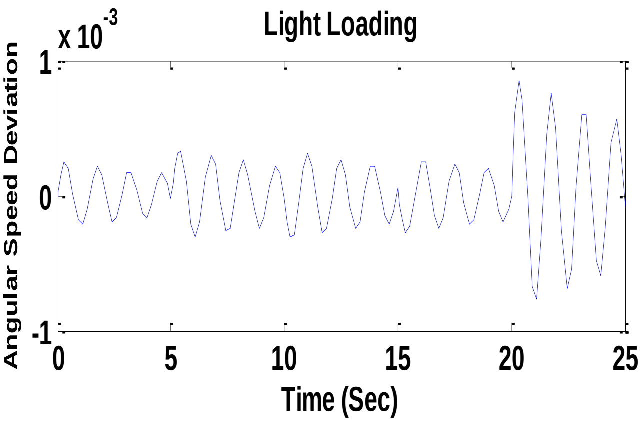

Fig 9(a): Simulation results of case (a)

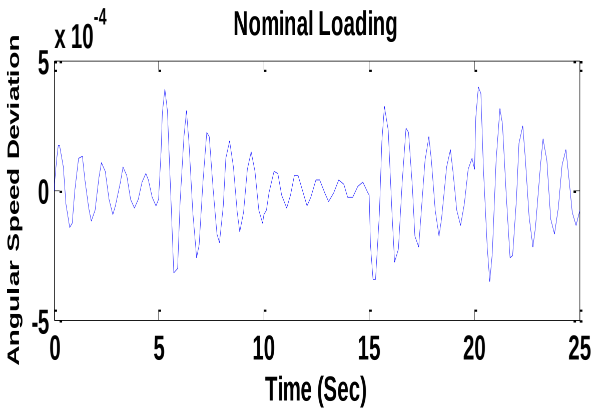

Fig 9 (b): Simulation results of case (b)

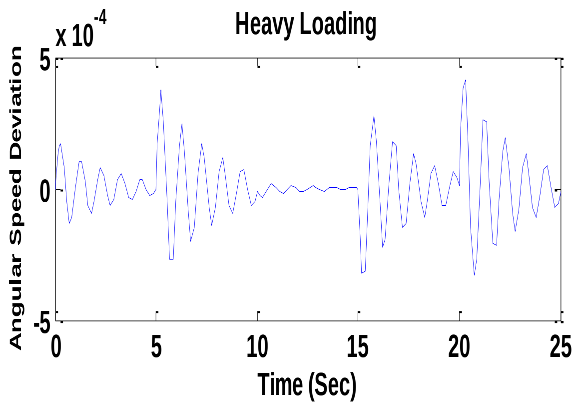

Fig 9 (c): Simulation results of case (c)

Fig 9(a)-(c): Angular Speed Deviation (Δω) Without H_∞ TCSC and Fuzzy PSS

Table 3. System parameter with different loading conditions

	Loading Conditions		
Parameter	(a) Light Loading (P=0.1pu)	(b) Nominal Loading (P=0.5 pu)	(c) Heavy Loading (P=1.0pu)
Angular Speed Deviation (Δω)	1.Smaller Overshoot (Mp)	1.Smaller Overshoot (Mp)	1.Smallest Overshoot (Mp)
	2.Peak Value = $8x10^{-5}$pu	2.Peak Value = $2.5x10^{-5}$pu	2.Peak Value = $1.8x10^{-5}$pu
	3.Settling Time (t_s) = 0.6 Sec	3.Settling Time (t_s) = 0.2 Sec	3.Settling Time (t_s) = 0.2 Sec
	4.Steady state error(e_{ss})=0	4.Steady state error(e_{ss})=0	4.Steady state error(e_{ss})=0

5. CONCLUSIONS

The hybrid H_∞ loop shaping TCSC & fuzzy PSS design for SMIB system has been proposed in this paper. The proposed hybrid controllers combine the advantages of H_∞ TCSC and Fuzzy Logic Controller and have an excellent capability in damping power system oscillations and enhance greatly the dynamic stability of the power system. The generator speed deviation (**Δω**) and acceleration (**dΔω /dt**) have been used as the feedback signal inputs. The simulation results show the robustness and superiority of the proposed control. It has been observed from the Fig 8(a)-(c) and Fig 9(a)-(c) that the system without fuzzy PSS and H_∞ TCSC is unstable but with hybrid H_∞ TCSC controller & fuzzy PSS the system gains stability quickly and robust stability of the power system against system uncertainties is ensured.

APPENDIX

Parameter values

Generator: M= 9.26 s., D = 0, Tdo' = 7.76, Wb=377

Exciter :(IEEE Type ST1): KA=50, TA=0.05 s.

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