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Fuzzy Compensation of Power-Voltage Interaction in a Combustion Turbogenerator

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Abstract: This paper introduces a compensation scheme for power-voltage interaction in a gas turbine driven power plant. The compensation scheme includes two fuzzy systems. The first fuzzy system compensates the effects of a change in voltage set-point over the power control loop. Complementarily, the second fuzzy system diminishes the effects of a change in power set-point over the voltage control loop. The compensation rules are basically obtained from the analysis of input-output interactions between the gas turbine and the electric generator. Rules are refined through simulation experiments using the full scope model of a 32 MVA combustion turbogenerator. Results show the appropriateness of the proposed fuzzy compensation scheme.

1. INTRODUCTION

Currently, generation of bulk power energy based on combustion turbogenerators (CTG) plays a major role worldwide. This is due to the advantages over other technologies, which include: low commissioning, maintenance and operation cost per MW, fast start-up to get into service and fast response to deal with load changes, possibility to use different fuels, as well as versatility to integrate high-efficiency combined cycles and cogeneration systems.

In a CTG, the mechanical energy developed by the gas turbine is converted into electric energy by the synchronous generator. Current control schemes for CTGs include independent control loops for the turbine and the generator. These schemes do not consider interaction between turbine and generator, which may cause oscillations in the power and voltage outputs. Oscillations may take the CTG out of the stability zone jeopardizing the energy supply.

To improve CTG performance it is necessary to compensate oscillations through the development of control systems that take into account the turbine generator interaction. Nevertheless, this interaction is not well covered in the technical literature; CTG models with complete turbine model do not have detailed generator model (Rowen, 1992, Delgadillo, 2002), and viceversa, CTG models with complete generator models do not have detailed turbine models (Kundur, 1994, Ong, 1997). Also, when interaction is considered both the turbine and generator models are oversimplified by not including major dynamics (Taiyou, 1997). This situation makes it difficult to analyze interaction and to design better control schemes.

This paper introduces a power-voltage interaction compensation scheme for a CTG. This scheme is designed from the interaction analysis with a complete 32 MVA CTG model (Hernandez, 2007). Compensation is carried out by means of two fuzzy compensators, one for the power control loop and another for the voltage control loop. The fuzzy power compensator diminishes interaction effects over the power output due to changes in voltage set-point. This compensator adds to the PID control signal of the power control loop. The fuzzy voltage compensator reduces the interaction effects over the voltage output due to changes in the power set-point, by modifying the PID control signal of the voltage control loop.

Section 2 provides a brief analysis of power-voltage interaction and shows the performance of current control schemes. Section 3 introduces the design of the fuzzy compensators, specifies the inputs and the membership functions for fuzzification and presents the fuzzy rules for each compensator. Section 4 presents results of simulation experiments to show the compensators performance. Finally, Section 5 draws the conclusions.

2. POWER-VOLTAGE INTERACTION AND CURRENT CONTROL SCHEMES

2.1 *Conventional PID-based CTG control schemes*

Typically, CTG control systems comprehend two major control devices: the turbine speed governor and the generator automatic voltage regulator (AVR). The speed governor regulates the turbine and generator speed of rotation during start-up, electric frequency when the CTG works in isolation

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feeding a local load or active power output when the CTG is connected to an electric grid. The AVR controls generator terminal voltage at start-up and when working isolated, and reactive power output when connected to the electric grid. In general terms, each of these devices implements a PID-based feedback control loop (Fig. 1). The governor implements the turbine power control loop, feeding a control signal to the fuel valve to increase or decrease fuel combustion as required for CTG power output regulation. The AVR implements the generator voltage control loop, providing the control signal to the excitation system to increase or decrease the field current as required to regulate the CTG terminal voltage.

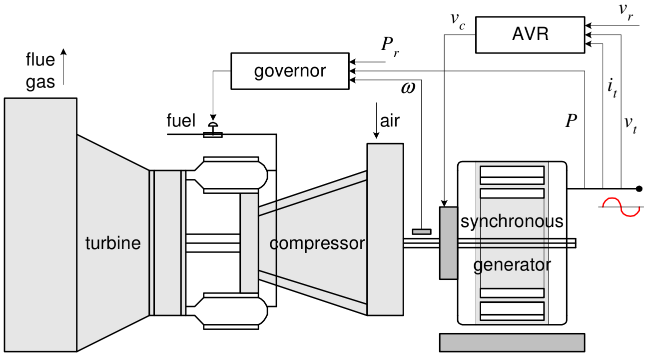

Fig. 1. Turbine governor and generator AVR controls.

In general terms, most of current CTG control schemes still assume that power and voltage control can be carried out independently, that is, with separate control loops. This is true in an approximate way in normal operating conditions at steady state and rated load. In another conditions, load variations make it evident an asymmetric coupling between both control loops. The effects of this coupling may decrease CTG performance, cause CTG instability and jeopardize electric energy supply in extreme cases.

2.2 Power-voltage interaction

In a single-shaft CTG, the turbine and the generator are mechanically coupled through the shaft. This way, the turbine spins the generator rotor and field windings at specific speeds, producing definite voltage and current at the stator windings through electromagnetic induction. The produced electric power is feedback to the turbine by the power control loop. Hence, a change in power will cause speed and voltage changes. Then, after the voltage change, the AVR in the voltage control loop will react to keep voltage output at the reference value, while the governor in the power control loop will try to regulate speed to cope with the change in power. This behaviour is demonstrated in Fig.2, which shows power step responses (plots a, c and e), and their effect over the voltage (plots b, d and f) at three different points of operation. Point I (plots a and b) is low load, Point II (plots c and d) is half load, and Point III (plots e and f) is rated load, as summarized in Table 1. On the other hand, Fig. 3 shows voltage step responses (plots a, c and e) and their effect over the power output (plots b, d and f) at the same points of operation.

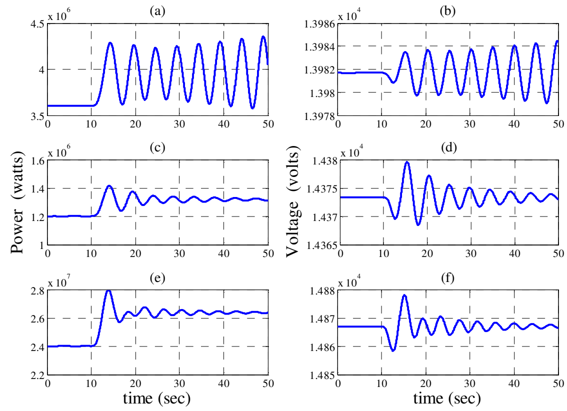

Fig. 2. Step in power and interaction effect on voltage.

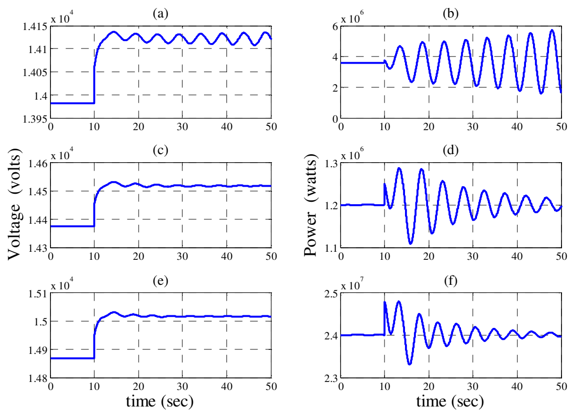

Fig. 3. Step in voltage and interaction effect on power output.

Table 1. Test points

Point	Power (% rated)	Power (MW)	Power factor
I	15	3.6	0.8 lagging
II	50	12	0.8 lagging
III	100	24	0.8 lagging

It can be seen that, with the conventional PID-based control scheme, a change in power reference may cause significant oscillations in the generator terminal voltage, and a change in voltage reference may cause large oscillations in the CTG power output. The effects of control loop interaction due to CTG coupling dynamics are clear enough; interaction effects in Point I (low load) may be large enough to cause instability (Plots a and b). Voltage settling-time after a step in voltage reference is shorter than power settling time, since they depend on fast electric variables and large mechanical inertia, respectively. As a result the voltage control loop is way faster than the power control loop. It can also be seen that voltage reference changes have a relatively larger impact on power output than power reference changes have on voltage, which is due to the asymmetric coupling dynamics of the CTG. In addition, note that the power and voltage step-responses, as well as their interaction effects, vary with the point of operation; larger variations appear faraway from the point of operation where the PID controllers were tuned. This is due to the non-linear dynamics of the CTG.

3. DESIGN OF FUZZY COMPENSATORS

The compensation scheme being proposed consists of two fuzzy systems intended to diminish the oscillations caused by the interaction between the voltage and power control loops to improve CTG performance throughout its operating space. Each fuzzy compensator supplies a compensation signal that is added to the output of the AVR and governor. The result of each sum is provided to the excitation system and to the fuel valve, respectively. Fig. 4 presents the compensation scheme. A major issue of this approach is that the design of the interaction compensator is carried out from the analysis of the error and control signals of the voltage and power control loops, with no need of a mathematical model describing the non-linear and coupling dynamics of the CTG, as required by other compensation methods (Garduno and Lee, 2005).

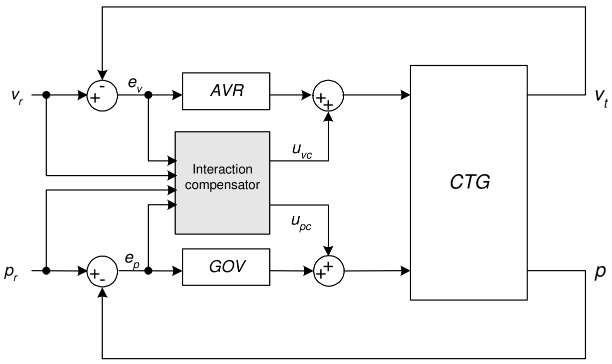

Fig. 4. Power-voltage compensation scheme for CTG.

2.3 *Power fuzzy compensator*

Inputs to the power fuzzy compensator are determined first. In this regard, after a voltage reference step the voltage error provides good information about the power error evolution (Fig. 5). Hence, the rate of change of the voltage error signal is taken as an input to the power fuzzy compensator.

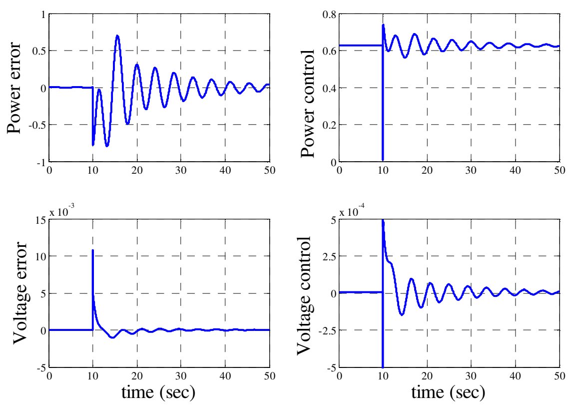

Fig. 5. Power and voltage error and control signals.

On the other hand, the power fuzzy compensator must only work after a change in the voltage reference. To assure this, the V_r-V_n variable is also defined as an input, where V_r is the voltage reference and V_n is the initial CTG operating voltage. The output of the power fuzzy compensator is named U_{pc}.

The power fuzzy compensator is implemented as a two-input-one-output Sugeno fuzzy system with constant consequent inference rules. The universes of discourse are determined after several simulation experiments, as well as membership functions for input fuzzification (Fig. 6).

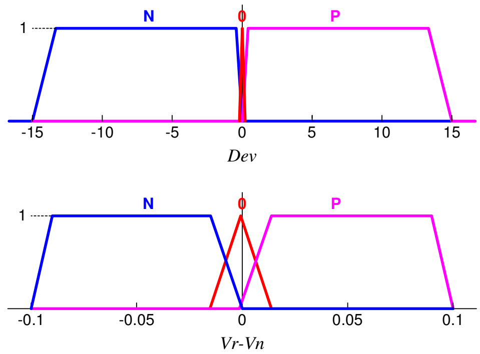

Fig. 6. Membership functions for power fuzzy compensator.

The inference rules have the form:

$$\textit{If Dev is \_\_ and } V_r - V_n \textit{ is \_\_, then } U_{pc} = \_\_.$$

Table 2 summarizes the inference rules of the power fuzzy compensator.

Table 2. Power fuzzy compensator knowledge base

Vr-Vn \ Dev	N	0	P
P	-0.08	-0.16	-0.3
0	0	0	0
N	0.3	0.16	0.08

2.4 *Voltage fuzzy compensator*

Input selection for the voltage fuzzy compensator is made the same way as for the power fuzzy compensator. However, in this case inference rules are defined for three load zones (low, half and rated) and required inputs depend on the load zone. Inputs include: e_p is power error, De_p is rate of change of power error, e_v is voltage error, P_r-P_n is the difference between the power reference, P_r, and the initial power value, P_n, which also defines the load zone at which the CTG is currently working. The voltage fuzzy compensator output is labelled U_{vc}.

The voltage fuzzy compensator is realized as a five-input-one-output Sugeno fuzzy system with constant consequent inference rules. As before, the universes of discourse, and thr membership functions for input fuzzification, are determined after performing several simulation experiments (Fig. 7). There is three different forms of inference rules to be used depending on the load zone, characterized by P_n:

If P_n is A and P_r–P_n≠0 and De_p is __ and e_v is __, then Uvc = __.
If P_n is B and P_r–P_n≠0 and e_p is __ and e_v is __, then Uvc = __.
If P_n is C and P_r–P_n≠0 and e_p is __, then Uvc = __.

Tables 3, 4 and 5 summarize the knowledge base of the voltage fuzzy compensator. Inference rules can be easily composed for each load zone. This approach reduces the number of rules of the knowledge base.

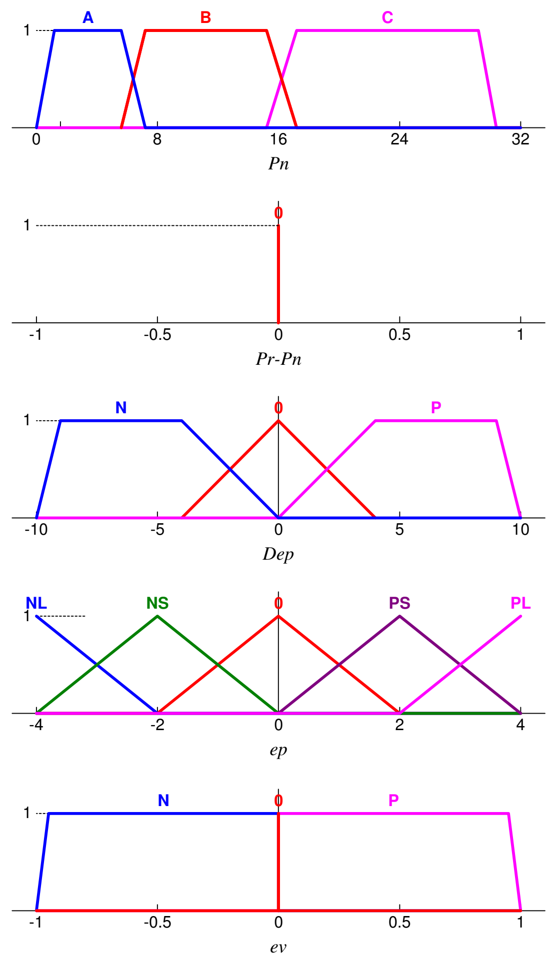

Fig. 7. Membership functions for voltage fuzzy compensator.

Table 3. Voltage fuzzy compensator knowledge base for low-load zone (P_n is A)

$Dep \setminus e_v$	N	0	P
P	-0.04	0	0.04
0	-0.03	0	0.03
N	0.04	0	-0.04

Table 4. Voltage fuzzy compensator knowledge base for half-load zone (P_n is B)

$e_p \setminus e_v$	NP	0	PP
P	0	0.005	0.005
0	0.005	0	-0.005
N	0	-0.005	-0.005

Table 5. Voltage fuzzy compensator knowledge base for rated-load zone (P_n is C)

e_p	NG	NP	PP	PG
Uvc	-0.001	-0.0004	0.0004	0.001

2.5 Power-voltage fuzzy compensator

A block diagram of the power-voltage fuzzy interaction compensator is presented in Fig. 8, which shows all inputs and outputs for both, the power fuzzy compensator and the voltage fuzzy compensator.

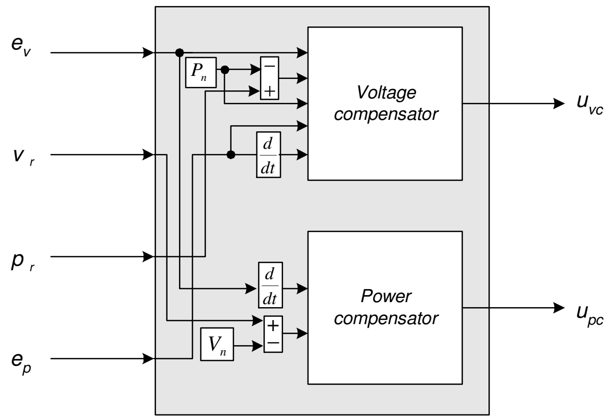

Fig. 8. Power and voltage error and control signals.

4. SIMULATION EXPERIMENTS

This section presents the results of simulation experiments aimed at demonstrating the performance of the CTG equipped with the interaction compensator. Experiments are the response to step changes in voltage and power references at the same points of operation defined in Table 1.

2.6 Power interaction compensation

Figs. 9 and 10 show that after a change in voltage reference at low-load (Point I), the uncompensated responses (UR dashed plot) oscillate and become unstable, while the responses obtained using the interaction compensator or compensated responses (CR continuous plot) become stable after the initial oscillations due to the change of voltage reference. Figs. 11 and 12 show the results of the same test at half-load conditions (Point II). Both compensated and uncompensated responses are stable, but responses with the interaction compensator settle in approximately half the time. Figs. 13 and 14 show that interaction effects from the voltage control loop to the power control loop have been diminished by a large amount with the power interaction compensator.

In general, the power fuzzy compensator grants good performance: decreases oscillations after changes in voltage reference, shortens the settling times and stabilizes the CTG response at unstable points of operation.

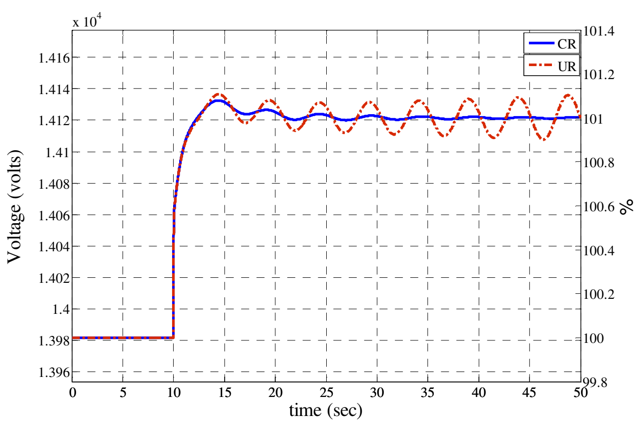

Fig. 9. Voltage response to voltage reference step in Point I.

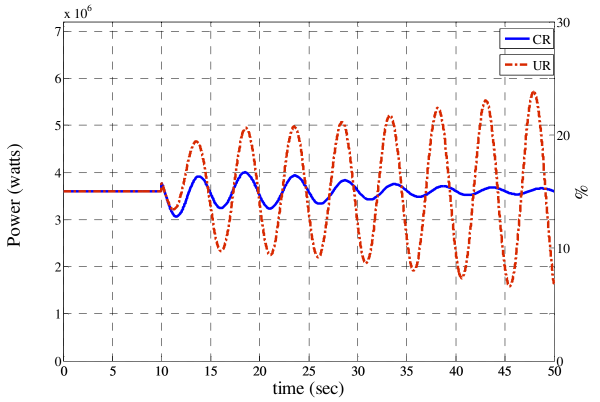

Fig. 10. Power response to voltage reference step in Point I.

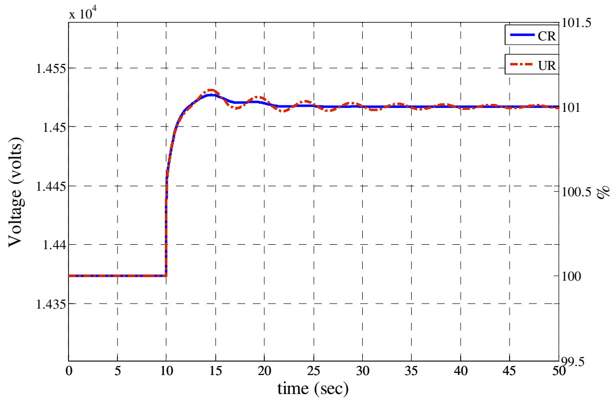

Fig. 11. Voltage response to voltage reference step in Point II.

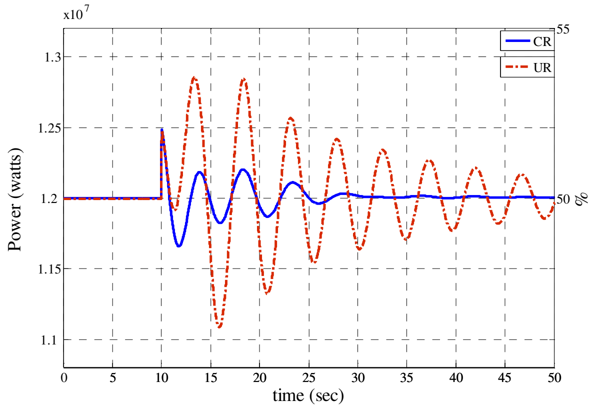

Fig. 12. Power response to voltage reference step in Point II.

2.7 *Voltage interaction compensation*

Figs. 15 and 16 show that the voltage fuzzy compensator stabilizes the CTG response at low load. Figs. 17 and 18 show the CTG response at Point II. The power step response settles faster with the voltage fuzzy compensator, and the effect of interaction over the voltage control loop is largely decreased. Figs. 19 and 20 show the CTG response at Point III to a step in power reference. The power response is about the same for both control schemes, while the interaction over the voltage control loop is almost completely removed.

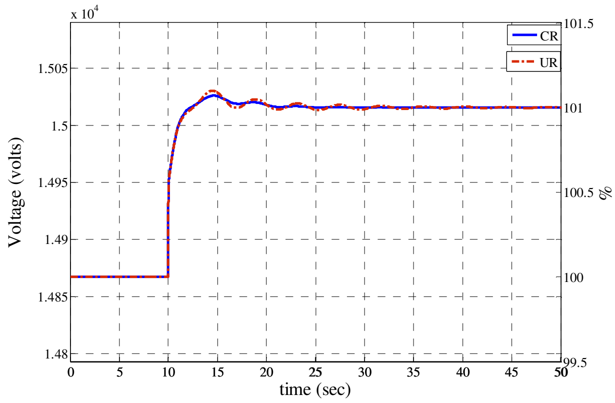

Fig. 13. Voltage response to voltage reference step in Point III.

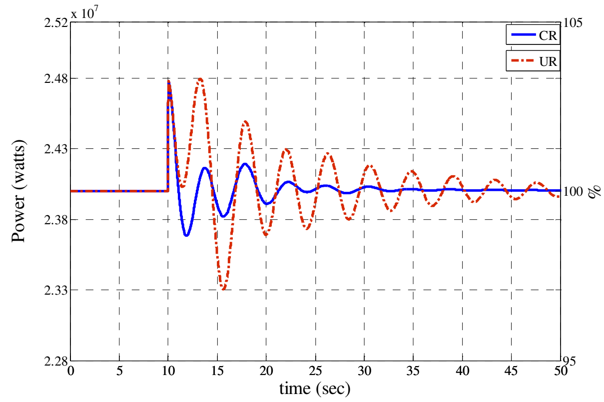

Fig. 14. Power response to voltage reference step in Point III.

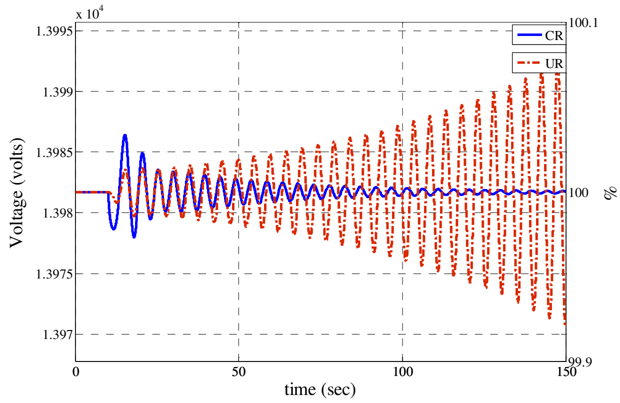

Fig. 15. Voltage response to power reference step in Point I.

From the previous results, it can be said that the voltage fuzzy compensator has an excellent performance close to the rated point of operation, where interaction oscillations are almost eliminated. At half-load conditions, reduction of voltage oscillations decreases power step response oscillations too. At low load the voltage fuzzy compensator stabilizes the CTG.

6. CONCLUSIONS

This paper presented a power-voltage fuzzy interaction compensator for a CTG. The scheme is based on two Sugenotype fuzzy systems that are designed from the analysis of the CTG responses to step changes in the power and voltage references. There is no need for a CTG mathematical model.

Results of simulation experiments using a full-scope detailed model of a 32 MVA CTG clearly show that performance is improved over that of a conventional PID-based control scheme. Oscillations due to control loop interaction decrease meaningfully or may be almost eliminated. Settling times of step responses are approximately 50% shorter. Finally, unstable behaviour at low load conditions is eliminated.

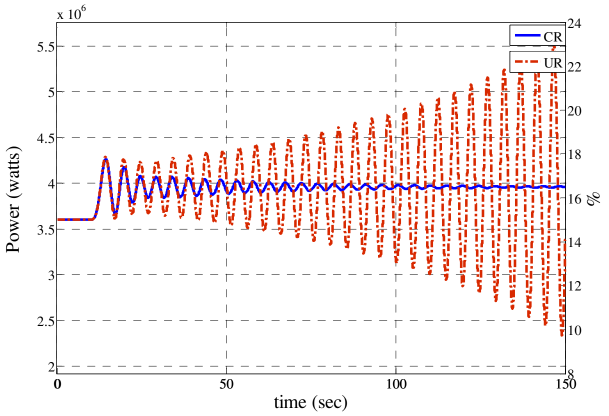

Fig. 16. Power response to power reference step in Point I.

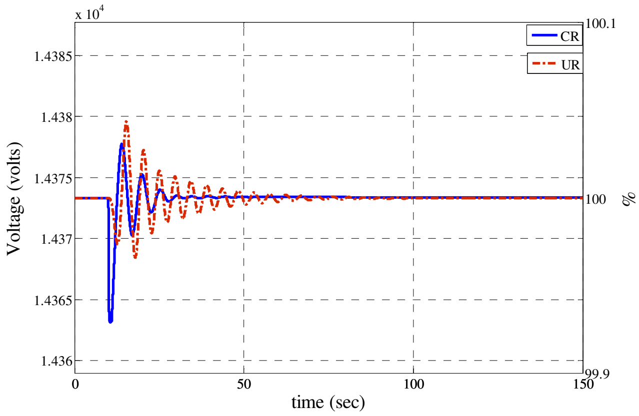

Fig. 17. Voltage response to power reference step in Point II.

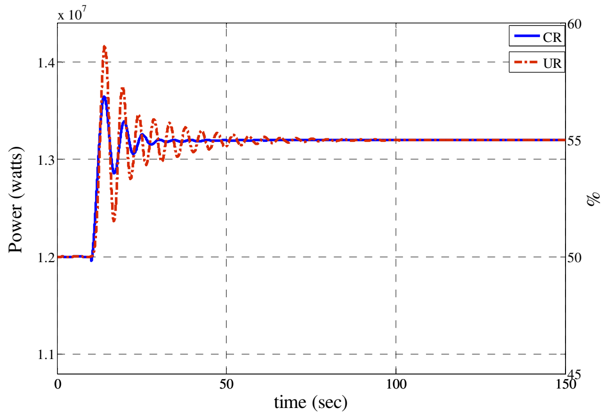

Fig. 18. Power response to power reference step in Point II.

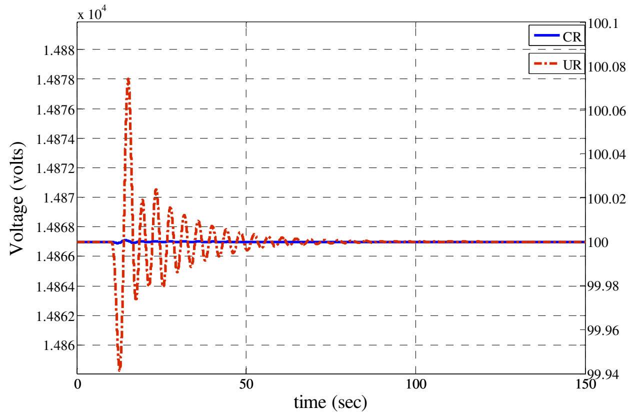

Fig. 19. Voltage response to power reference step in Point III.

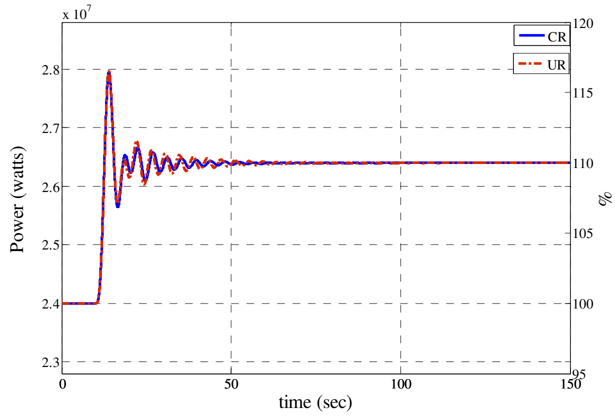

Fig. 20. Power response to power reference step in Point III.

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