Testing of the FDC based Excitation Current Regulator

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Abstract—**The subject of this paper is generator control. The new type of an excitation controller based on Forced Dynamics Control is presented. The proposed control method in contrary to traditional ones is model-based control technique. The operation of proposed excitation current regulator (ECR) was tested using signals generated in Simplorer. Various generator operating scenarios were considered. The most important were presented and discussed.**

Keywords-synchronous generator; excitation current regulator; generator control; Forced Dynamics Control

I. Introduction

The primary control of system voltage takes place at generators terminals at power stations. This is the reason why generators or alternators used to produce electrical energy must be equipped with generator controllers. These control units are responsible for keeping the output voltage at specified level under different operating conditions (e.g. excitation, various load levels).

In generator terminal voltage control one can distinguish two types of regulation. The first one is automatic control. In this type of control the Automatic Voltage Regulator (AVR) forces the generator terminal voltage to follow the reference value (basing on deviation of terminal voltage from reference value the control signals are generated). The second type of control is so-called "manual" control where Excitation Current Regulator is used. This type of controller makes the excitation current follow the current reference value. In practical applications both types of controllers are used in parallel.

In the paper the idea of using Forced Dynamics Control theory to design generator voltage controllers is discussed. The new controller based on FDC control approach is described in following sections. The performance of presented FDC regulator has been tested with signals generated using Simplorer. Examples of testing results are presented, discussed and compared to ones obtained for the traditional ECR.

II. Excitation Current Regulator

This type of regulation is so-called „manual control", where the controller forces the demanded value of the field current. Basing on the deviation of measured value of field current from the reference value the exciter voltage is calculated. It should be mentioned here, that the terminal voltage of the synchronous generator is the function of generator field current. In the analyzed case, the field current value of 377 A corresponds to the terminal voltage value of 15.75 kV.

The reference for comparison is the Excitation Current Regulator which controls the thyristor rectifier that is connected to the excitation system of the generator. The general scheme of this static excitation system is presented in Figure 1.

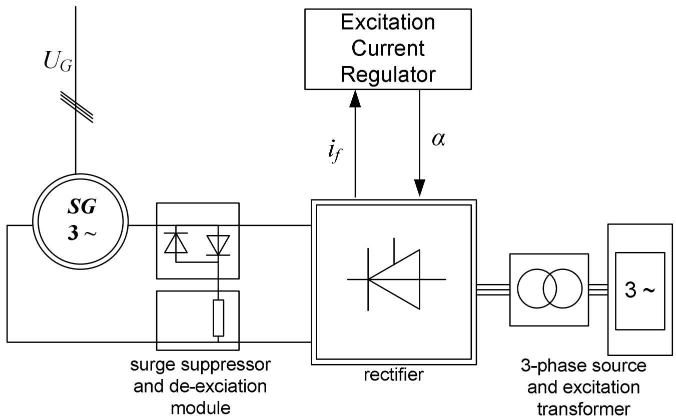

Figure 1. The structure of the static excitation system.

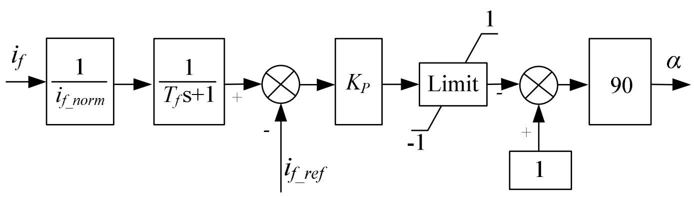

Figure 2. The scheme of the ECR

The output of the employed Excitation Current Regulator is the angle α that is the steering signal for the thyristor rectifier. This signal is generated basing on the deviation of the generator field current i_f from its reference value i_{f_ref} . Firstly the measured generator field current is normalized and filtered. The reference value has to be normalized too. The deviation of the field current is amplified by the gain K_p and goes to the limiter. The regulator output signal is obtained by subtracting the output of the limiter from 1 and multiplying by 90°. The value of the angle α varies from 0° to 150°. The scheme of the employed ECR is presented in the Figure 2.

III. ECR Based on Forced Dynamics Cobtrol

In contrary to traditional control structures FDC is a model-based control technique. The control technique is described in detail in [2].

Before the control algorithm can be developed, the equations of mathematical model of the synchronous generator must be presented. The general model of the synchronous generator in d-q co-ordinate system, which is coupled to the moving part of the machine is as follows:

$$u_d = -\frac{d\psi_d}{dt} - \psi_q \frac{d\gamma}{dt} - R_s i_d \quad (1)$$

$$u_q = -\frac{d\psi_q}{dt} + \psi_d \frac{d\gamma}{dt} - R_s i_q \quad (2)$$

$$u_f = \frac{d\psi_f}{dt} + R_f i_f \quad (3)$$

$$\psi_d = L_d i_d \quad (4)$$

$$\psi_q = L_q i_q \quad (5)$$

$$\psi_f = L_f i_f \quad (6)$$

where u_d, u_q and i_d, i_q are stator voltage and current components, u_f and i_f are field voltage and current, ψ_d, ψ_d are stator magnetic flux components, ψ_f is field magnetic flux, R_s and R_f are stator and field resistances, L_d, L_q and L_f stator inductance components and field inductance, m_1 is the amplitude of mutual inductance of phase a and field circuit. The subject of this paper is current and voltage control, so that only an electrical part of the mathematical model is presented [1].

In considered case only excitation circuit is analyzed – equation (3). Equation (7) is the required state differential equation:

$$\frac{di_f}{dt} = \frac{1}{L_f}\left(u_f - R_f i_f\right) \quad (7)$$

The controlled variable is field current *if*, the control variable is field voltage u_f. One can see that the controlled variable appears on the right hand side of the equation (7) so that the rank of the plant is just $r = 1$. Then the desired closed loop differential equation would be as follows:

$$\frac{di_f}{dt} = \frac{3}{T_{si}}\left(i_f - i_{f\_ref}\right) \quad (8)$$

where i_f is the measured excitation current, i_{f_ref} is the excitation current reference input and T_{si} is the settling time of current control loop [2]. Equating the right hand sides of equations (7) and (8):

$$\frac{1}{L_f}\left(u_f - R_f i_f\right) = \frac{3}{T_{si}}\left(i_f - i_{f\_ref}\right) \quad (9)$$

leads to the FDC control law descried by:

$$u_f = L_f \frac{3}{T_{si}}\left(i_f - i_{f\_ref}\right) + R_f i_f \quad (10)$$

All the parameters of the FDC controller are the parameters of the synchronous generator that is the controlled plant. The only parameter that should be modified by the user is the time constant T_{si}. According to the Forced Dynamics Control theory changing this parameter of the regulator makes it possible influence the dynamics of the system. The scheme of the designed FDC field current controller is depicted in Figure 3.

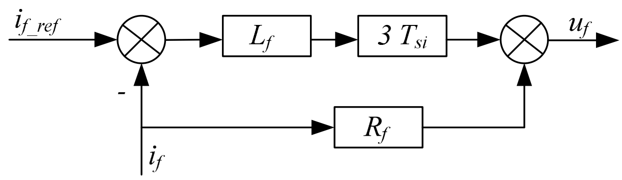

Figure 3. The scheme of Excitation Current Controller based on FDC

IV. Simulation Studies

The proposed FDC controller an the traditional ECR were tested using Simplorer in different testing scenarios. In order to analyze the performance of the proposed exciter regulator following testing scenarios were considered:

- excitation
- de-excitation,
- change of the reference value.

All testes were performed for idle running of the generator.

A. Simulation parameters

In the simulation studies a model of a synchronous generator for steam turbines was used – generator type TLRI 115/36. The parameters of the synchronous generator are presented in the Table I.

In order to conduct simulations in Simplorer, the parameters of the generator rotor must be transformed to the stator side. The field voltage and field current for the idle run that were used in simulations can be calculated using equations (11) and (12) [3]:

$$U_{f0SIM} = \frac{U_n\sqrt{2}\cdot r_{fd}}{\sqrt{3}\cdot x_{hd}} \quad (11)$$

$$I_{f0SIM} = \frac{I_n\sqrt{2}}{x_{hd}} \quad (12)$$

Real parameters of the rotor and stator related values calculated according to equations (11) and (12) are presented in the Table II .

TABLE I. PARAMETERS OF THE SYNCHRONOUS GENERATOR TLRI 115/36 [3]

Generator type TLRI 115/36	
S_n	206 MVA
$\cos \varphi$	0,8
f	50 Hz
U_n	15,75 kV
I_n	7551 A
U_{f0}	95 V
I_{f0}	377 A
U_{fN}	291 V
I_{fN}	1153 A
U_{fd}	523 V
x''_d	0,1666 p.u.
x'_d	0,2432 p.u.
x_d	2,434 p.u.
x_{hd}	2,292 p.u.

TABLE II. PARAMETERS OF THE GENERATOR ROTOR [3]

Parameter	Real value	Stator related values
U_{f0}	95 V	3,4 V
I_{f0}	377 A	4660 A
r_f	252 mΩ	0,6 mΩ

B. *Testing results*

In this section the performance of the proposed FDC Excitation Current Regulator and the performance of the traditional ECR are presented. Figures 4-13 depict results obtained in excitation – de-excitation testing scenario. Signals significant in controller analysis, such as generator terminal voltage and its deviation from the reference value, generator field voltage, generator excitation field current and its deviation from the reference value are presented. The signals obtained for the FDC ECR can be compared to ones obtained for the traditional ECR.

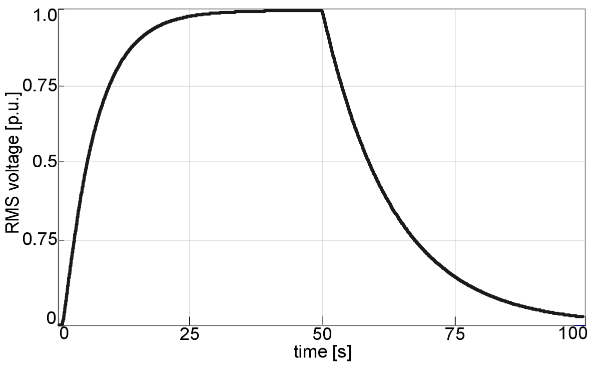

Figure 4. Generator terminal voltage for a case of excitation and de-excitation for the FDC based ECR

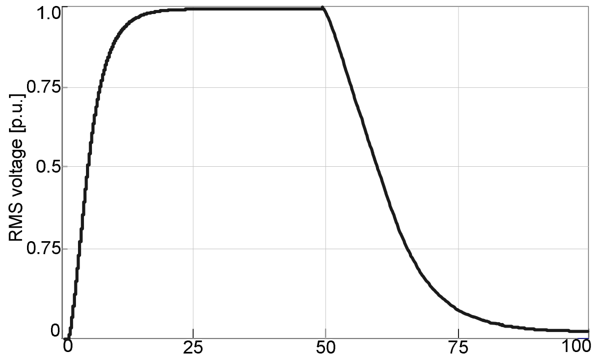

Figure 5. Generator terminal voltage for a case of excitation and de-excitation for the traditional ECR

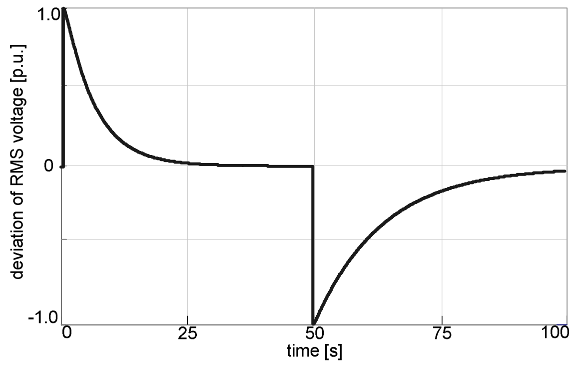

Figure 6. Deviation of generator terminal voltage for a case of excitation and de-excitation the FDC based ECR

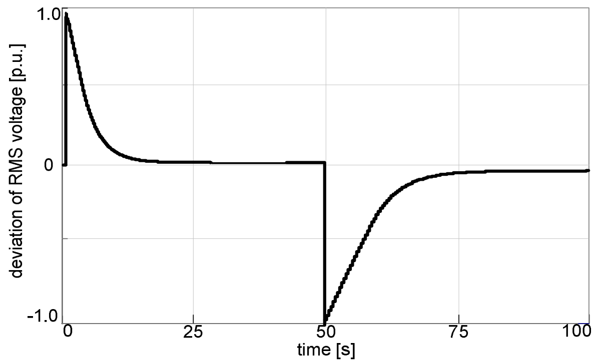

Figure 7. Deviation of generator terminal voltage for a case of excitation and de-excitation for the traditional ECR

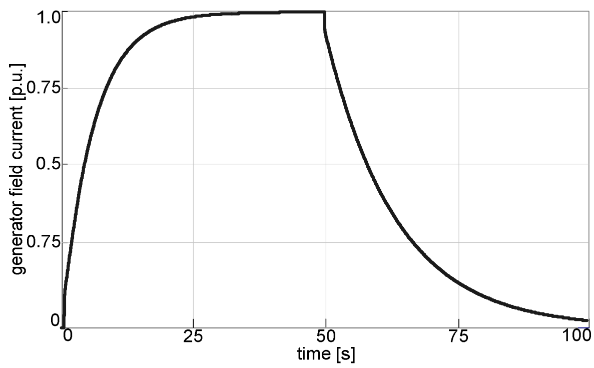

Figure 8. Generator field current for a case of excitation and de-excitation for the FDC based ECR

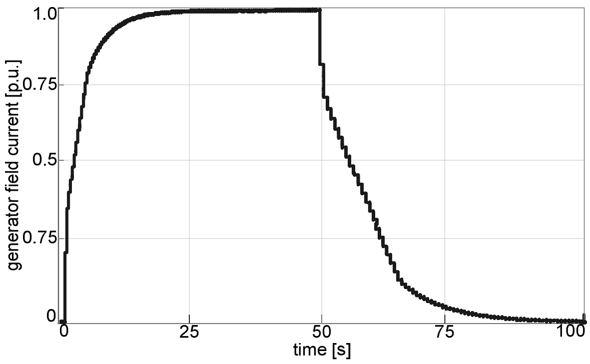

Figure 9. Generator field current for a case of excitation and de-excitation for the traditional ECR

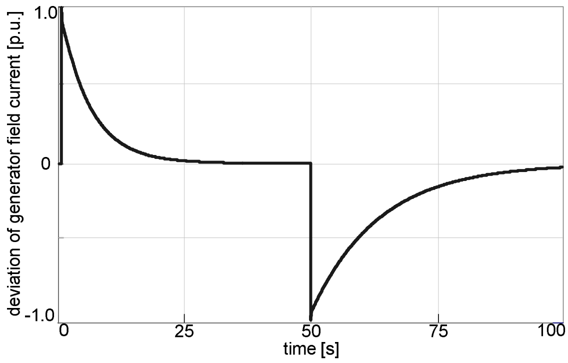

Figure 10. Deviation of generator field current for a case of excitation and de-excitation for the FDC based ECR

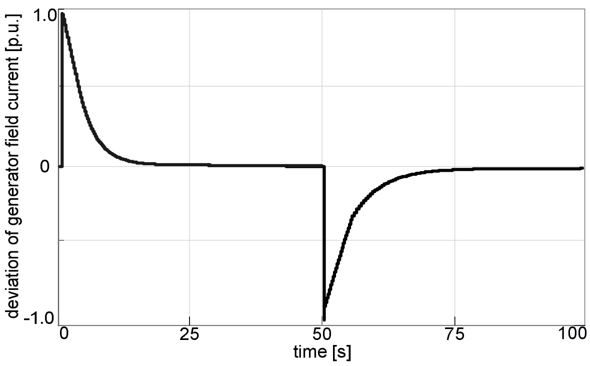

Figure 11. Deviation of generator field current for a case of excitation and de-excitation for the traditional ECR

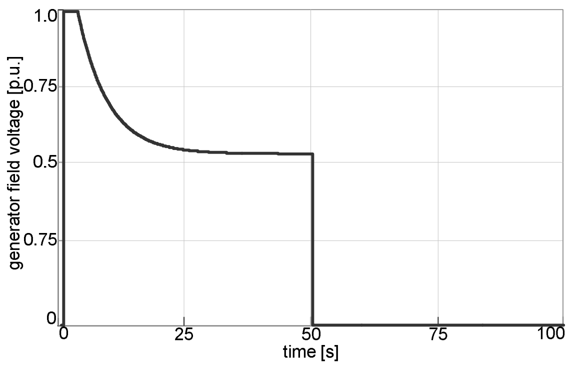

Figure 12. Generator field voltage for a case of excitation and de-excitation for the FDC based ECR

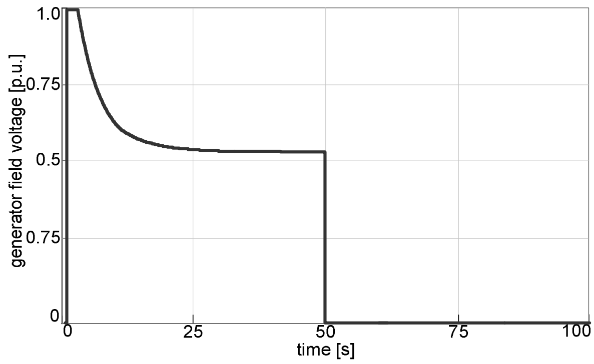

Figure 13. Generator field voltage for a case of excitation and de-excitation for the tradiitional ECR

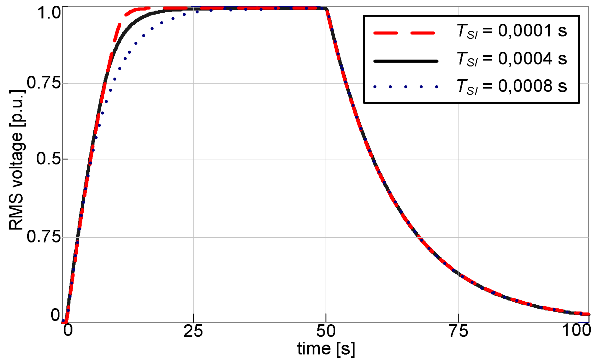

Figure 14. Generator field voltage for a case of excitation and de-excitation for the FDC based ECR

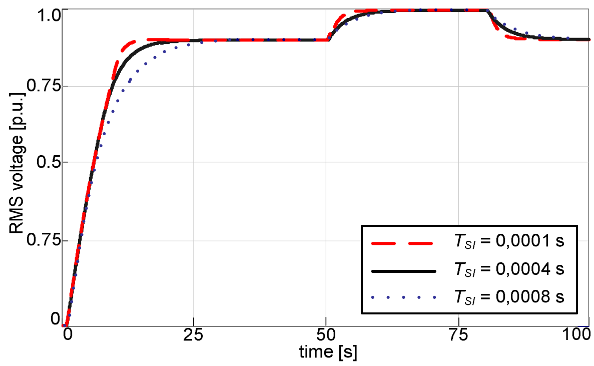

Figure 15. Generator field voltage for a case of changes of the reference value for the FDC based ECR

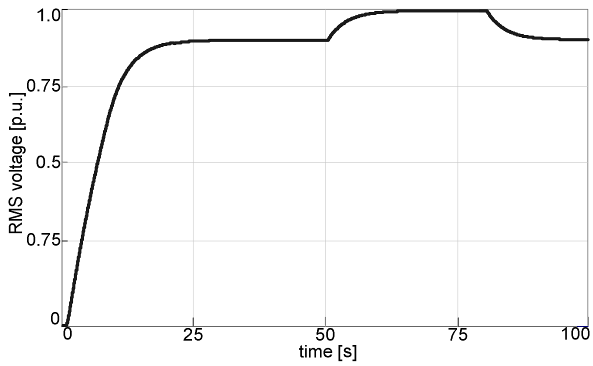

Figure 16. Generator field voltage for a case of changes of the reference value for the traditional ECR

In order to present the possibility of controlling the dynamics of the system, several tests for different FDC controller time constants T_{SI} were performed.

The case of excitation – de-excitation is presented in the Figure 14. This is the same testing scenario that was pictured in Figures 3-14. It can be noticed that the behaviour of the FDC regulator is similar to the traditional one. When the traditional ECR is used it is not possible to control the dynamics of the system. In the case when the FDC controller is used, one can observe different system dynamics that depends on the value of the controller time constant. For the smaller value of the time constant $T_{SI.}$ the RMS voltage reaches its demanded value faster. The bigger the value of $T_{SI.}$ is, the dynamics of the system is lower. No change in the system dynamics is observed in the de-excitation. This is probably caused by the limitation of the de-excitation module.

The second considered example was the scenario when the reference value is changed. The obtained results for three different regulator time constants are presented in Figure 15. The performance of the FDC based ECR can be referred to the performance of the traditional ECR that is depicted in Figure 16. The change of the dynamics can be observed both in case of increasing and decreasing the reference value. The same as it was observed previously, for the smaller value of the time constant $T_{SI.}$ the RMS voltage reaches its demanded value faster.

Conclusions

In the paper the excitation current regulator based on Forced Dynamics Control is presented. As a reference for comparison , to confirm the correct operation of the FDC controller, the traditional ECR was used.

The idea of the Forced Dynamics Control is to control the plant with the dynamics that can be chosen by the user. In contrary to the traditional control approaches, FDC is model based control method. There is no need to calculate or adjust the controller parameters. The only parameter that should be modified is the controller time constant T_{SI}. All the other regulator parameters are the parameters of the controlled plant. This is the reason why the mathematical model of the plant, in this case the model of the synchronous generator must be carefully formulated. Due to space limitation only the main premises of the FDC and the most important steps of designing FDC controller are presented.

Comparative analysis of the FDC ECR and the traditional ECR confirmed the correct operation of the proposed controller. The simulation tests presented in this paper proved that application of FDC method in excitation current control makes it possible directly influence the dynamics of the system.

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