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Load Angle Control of a Synchronous Generator

***Abstract**. This paper presents a new control structure for the synchronous generator excitation control in its capacitive operating area. The proposed method enables the generator to operate stably close to the stability limit, extending its capacitive operating area. As to generator stability, the main variable is the generator load angle, hence the proposed method suggests using a load angle controller along with a voltage controller. The proposed algorithm has been implemented in a digital system based on a signal processor and has been experimentally verified on a lab model.*

***Streszczenie.** W artykule zaprezentowano nową strukturę sterowania generatorem synchronicznym obciążonym pojemnościowo. Dla zapewnienia stabilności zastosowano sterowanie z uwzględnieniem kąta obciążenia. (**Sterowanie kątem obciążenia w generatorze synchronicznym**)*

Keywords: load angle control, synchronous generator, excitation control
Słowa kluczowe: generator synchroniczny, sterowanie, kąt obciążenia.

Introduction

In its capacitive operating area, the generator tends to fall out of synchronism with the network, so there has to be a limit for the maximum power with which the generator can be loaded without falling out-of-step (static limit of stability, Fig. 1). The ability to hold the generator in synchronism in case of a disturbance decreases as the generator operating point approaches the stability limit. The common solution to this problem is limiting the generator operating area to a point far enough from the stability limit by limiting the minimal excitation current and the maximum synchronous generator load angle (practical stability limit) [1, 2, 3]. This is a way to ensure stable generator operation in the case of sudden changes in the power system, such as a short circuit etc., but at the same time, the permanent operating area of a capacitively loaded generator is reduced, which, under the conditions of a deregulated power market, causes economic losses. The variable that shows how close the generator is to the static stability limit is the load angle. It raises with the active load and the larger the angle, the closer the generator gets to the stability limit and the greater the danger for the generator to fall out of synchronism. Load angle is defined as the angle between the induced voltage E_q and the AC network voltage V_m and it rises proportionally to the growth of the active load [1, 4].

The active power of a generator with salient poles, connected to a power system, is determined by expression [1, 5]:

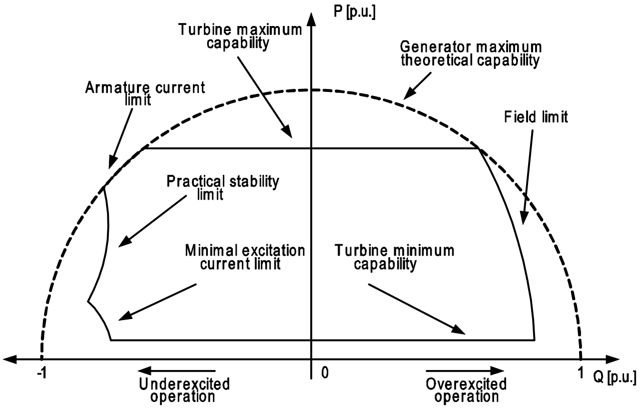

Fig. 1. Operating limitations in synchronous generator P-Q diagram

$$(1)\quad P=\frac{V_m E_q}{X_d+X_e}sin\delta+\frac{V_m^2}{2}\frac{X_d-X_q}{(X_d+X_e)(X_q+X_e)}sin2\delta$$

where E_q is the induced voltage, V_m is the AC network voltage, X_d and X_q are synchronous reactances, X_e is the reactance of the transformer and transmission lines, and δ is the load angle. Although the generator with a cylindrical rotor and a generator with salient poles can be loaded up to the critical angle, for the sake of safety of their permanent operation with limitations to the minimal excitation current, there must be a defined practical stability limit i.e. maximum load angle limit, with a certain power reserve, which will not allow permanent generator operation near the critical point.

Structure of synchronous generator excitation control system

The synchronous generator excitation system realized on a laboratory model contains a digital control system, measurement elements and an IGBT converter to provide excitation current. The digital control system is based on a Texas Instruments TMS320F2812 signal processor. Fig. 2 shows the structure of an 83 kVA synchronous generator excitation control system, which includes an excitation current controller, a voltage controller and a reactive power controller of the generator.

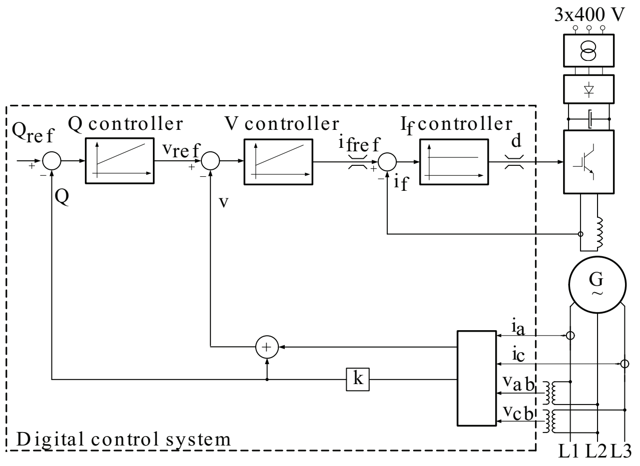

Fig. 2. Structure of synchronous generator excitation control system

The reactive power controller is used depending on the demands of the power system on an individual generator [6, 7, 8]. The reactive power controller and the voltage controller are proportional-integral controllers and the excitation current controller is a proportional controller. The reactive power controller is superordinate to the voltage controller which is superordinate to the excitation current controller. The reactive power controller output is the reference value of the generator voltage *v_{ref}*, the voltage controller output is the reference value of excitation current *i_{fref}*, and the excitation current controller output is the conducting period for the transistors of the converter *d*. All controller outputs are limited. The measured variables are excitation current, generator voltage, generator current and generator load angle. The generator voltage characteristic is compensated by a step up in voltage feedback with a step up in the generator reactive power. The compensation is turned on when the generator is connected to a power system and ensures a decreasing characteristic of the generator voltage with the increase in reactive power.

Synchronous generator excitation control system with load angle controller

The structure of a synchronous generator excitation control system with a load angle controller added parallel to the voltage controller is shown in Fig. 3. The voltage and load angle controllers are never on at the same time but they alternate in controlling the excitation current. A proportional-integral load angle controller is used. In the moment of transition between the voltage controller and the load angle controller the voltage integrator state is placed into the load angle controller integrator which enables the transfer to take place between the load angle controller and the voltage controller without a step-change in the excitation current reference. The suggested algorithm does not allow the generator to fall out of synchronism due to the load angle increase caused by such disturbances, but instead the load angle controller is turned on and the excitation current increases. Thus the load angle is reduced and the generator moved away from the static stability limit.

The basic demands placed on an excitation system with a load angle controller are:

- adjusting load angle activity (turning on and off) in a way that will enable the operation of a capacitively loaded generator as close to the stability limit as possible,
- choosing a way to set the load angle controller reference value that will enable the safest load angle control,
- enabling uninterrupted transfers between the load angle controller and voltage controller activity periods,
- measuring the load angle (described in appendix A.1).

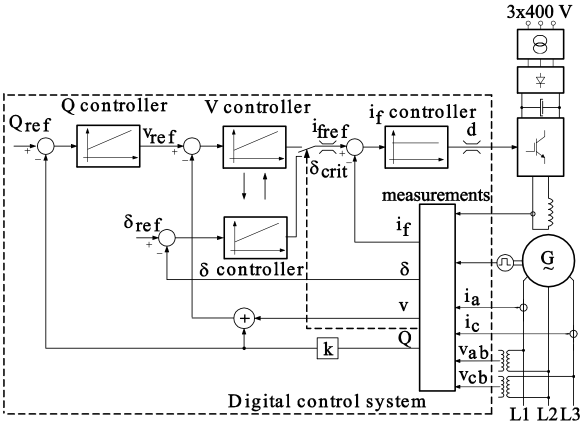

Fig. 3. Synchronous generator excitation control system with load angle controller

When the load angle controller is to be turned on and off is determined by means of hysteresis. When the load angle crosses the upper limit of hysteresis the load angle controller is turned on and the load angle is reduced to the reference value. The controller is turned off when the load angle drops below the hysteresis lower bound. This occurs when the control of the excitation current is again taken over by the voltage controller. Hysteresis limits are the limits of the load angle controller operation. In order to exit the load angle control the load angle controller reference value must be below the lower bound of hysteresis. The value chosen as the load angle controller reference value is 0 to make it possible for the generator to quickly move away from the stability limit when the load angle controller is active. Because of the character of the stability limit the generator critical angle changes depending on the operating point. In order to extend the permanent operating area of the capacitively loaded synchronous generator the hysteresis limits must not be fixed, but are adjusted depending on the operating point. Given that the critical angle at which the generator is in danger of falling out of synchronism is a break-over angle, in the suggested algorithm hysteresis limits are adjusted depending on the critical angle. Another problem that appears during the transition from angle control to voltage control is that of the reference value of the voltage controller. Namely, the load angle controller operates so as to increase the excitation current by reducing the load angle, increasing the voltage and reducing the generator capacitive reactive current. Before entering angle control, the voltage reference value, which also determines the reactive power taken by the generator, is assigned to the voltage controller. If that voltage reference value does not change while transferring back from load angle control to voltage control, the voltage controller will decrease the generator voltage to a value determined by the reference value which will again lead to an increase in the load angle and will turn the load angle control back on. The problem is solved by assigning the current generator terminal voltage value as the voltage controller reference value in the moment of transition from load angle control to voltage control.

The critical angle is defined as the load angle of the generator at stability limit. The critical angle changes as the operating point changes, i.e. when changes occur in the generator active and reactive power. The basic idea of the synchronous generator excitation control is that the load angle controller turns on when the generator approaches the stability limit, which is when the load angle approaches the critical angle. Therefore, it is crucial for the functioning of the algorithm to calculate the critical angle precisely. In order to do so, one must calculate the reference value of the induced voltage *E_{qref}* from expression [4]:

$$E_{qref} = \sqrt{\left(V_{ref} + \frac{Q_{ref}}{V_{ref}} X_q\right)^2 + \left(\frac{P_{ref}}{Q_{ref}} X_q\right)^2} \tag{2}$$

where *E_{qref}* is the induced voltage reference value, *V_{ref}* the generator voltage reference value, *Q_{ref}* the reactive power reference value and *P_{ref}* is the active power reference value, all in per unit values. The critical angle is determined by deriving equation (1) for active power and equaling the derivation to zero. The critical angle can be calculated from the expression:

$$\begin{aligned}\delta_{crit} = arccos(&\frac{1}{4V_m(X_d - X_q)}(-E_{qref}(X_q + X_e) + \\ &+\sqrt{(-E_{qref}(X_q + X_e))^2 + 8(V_m(X_d - X_q))^2}\ ))\end{aligned} \tag{3}$$

where the critical angle value is in degrees, and other values are in per unit.

The critical angle value is limited to 80 degrees thus determining the practical generator stability limit. The dependence of the critical angle on active and reactive power is shown in Fig. 4 for a synchronous generator with the nominal data given in appendix A.2.

Fig. 4 shows that the critical angle becomes smaller as reactive power increases and that the critical angle becomes larger as active power increases. The upper limit of hysteresis determines the allowed operation of the capacitively loaded synchronous generator, so attempts must be made to bring it as close as possible to the stability limit. It is, of course, also imperative that the load angle controller successfully returns the generator into the area of stability in case of any disturbances. If a fast excitation system is available, the upper limit of hysteresis (turning on the angle controller) can be set to the critical angle value as the optimal value. The lower limit of the hysteresis belt is the angle at which the load angle controller is turned off, which means that the load angle must be distant enough from the stability limit. The sufficient distance is that at which, after exiting the angle control, the voltage controller can damp other oscillations.

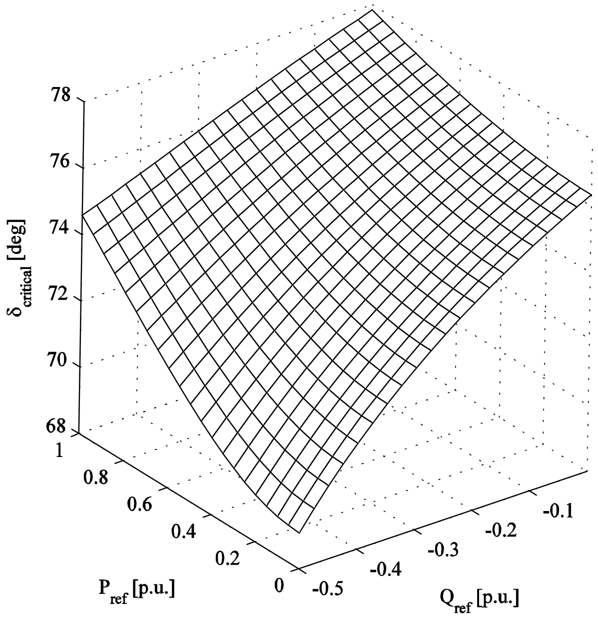

Fig. 4. Dependence of critical angle on generator active and reactive power

It should be noted that the hysteresis belt is wide enough, lest it should happen that the angle controller is turned on and off multiple times at transient states with great load angle oscillations. This is not a desirable occurrence because it leads to greater oscillations of the load angle. The lower bound of hysteresis is determined for different operating points for the examined system, the critical angle value being minus 20 degrees. Adjustments of the load angle controller are given in appendix A.3. It is important to stress that the load angle reference must be below the lower bound of the hysteresis belt. If the reference values were between the hysteresis upper and lower limits, the load angle would never drop below the lower bound and the load angle controller would never get turned off. The only option for turning the angle controller off in this case is reducing the active power reference value. However, that will not lead to the load angle controller being turned off because the load angle is reduced along with the active power; so the angle controller reduces the excitation current to the reference value. Therefore, the only way to exit the load angle control is to set the load angle controller reference value below the lower bound of hysteresis. The generator voltage reference value determines its reactive power. In case the load angle approaches the critical angle the suggested algorithm will increase the excitation current and thus reduce the reactive power below the sum determined by the voltage reference value. To enable an undisturbed transfer from load angle control to voltage control, in the moment of transfer from angle control a new reference value must be assigned to the voltage controller. Namely, the load angle controller brings the generator back into the area of stability by reducing the reactive power the generator sends to the network i.e. by increasing the generator voltage. When the transfer from load angle control to voltage control occurs, the excitation current control is again taken over by the voltage controller, which then tries to adjust the generator voltage to the voltage reference value. If there has been no increase in the voltage reference value, the voltage controller will reduce the excitation current i.e. increase the capacitive reactive power, which will again bring the generator closer to the stability limit and turn the load angle controller back on. If this problem is not solved, the angle controller and the voltage controller will be turned on and off, which would result in too many oscillations of all generator variables. The problem is solved by setting the voltage measured at that moment on the generator terminal as the reference value for the voltage controller in the moment of the transfer back into voltage control.

Experiments

The experimental validation of the excitation system operation of the synchronous generator with the aforementioned algorithms for voltage and load angle control was conducted on a laboratory model the structure of which is shown in Fig. 5.

The experimental setup consists of a digital control system based on a digital signal processor TI TMS 320F2812, a thyristor converter (100 kW) with an output current controller, two DC motors (one on each side of the generator) and a salient-pole synchronous machine (appendix A.4.). There are reactances between the generator and the power system which represent transmission lines. The two-quadrant IGBT AC/DC converter is used as an excitation current source. The rotor position is measured with an incremental encoder.

The excitation control system with a load angle controller was tested under the conditions of a generator voltage reference step change and a mechanical power reference step change. Each experiment was performed on an excitation control system with and without a load angle controller. The operation of the load angle controller was evaluated based on a comparison of the results obtained. The measured load angle, the estimated load angle (estimated by the estimation method given in [9]) and the critical load angle as well as the limits of the angle controller are expressed in degrees. The angle controller activation signal achieves the value one when the angle controller is on and zero when it is off. Other variables are expressed in per unit.

Because this paper deals with tests of the operation of the generator near the capacitive stability limit, the voltage reference value change is negative: it changes from 0.9 p.u. to 0.7 p.u. While operating at 0.9 p.u. voltage value the generator is at a stable operating point and all physical variables are stable and do not oscillate.

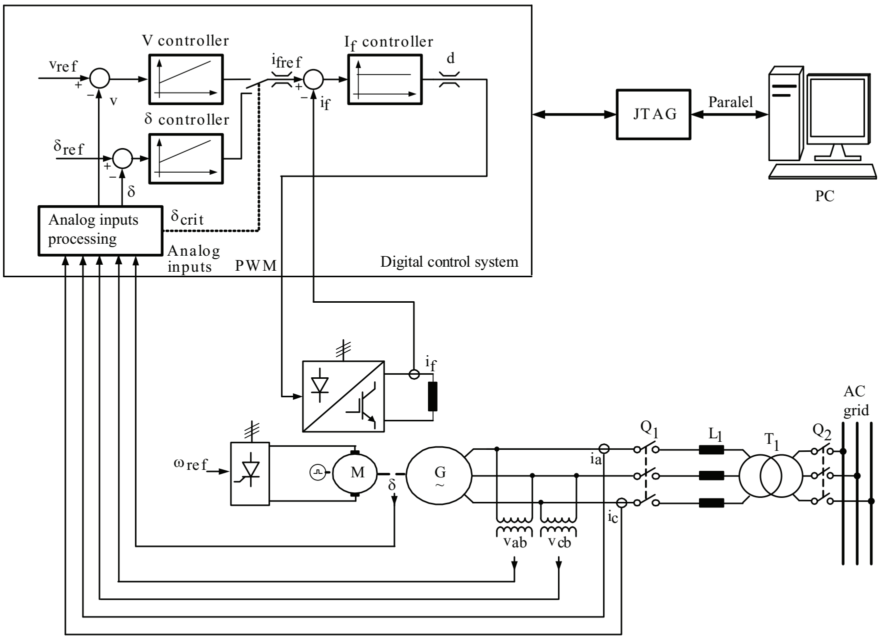

Fig.5. Experimental setup

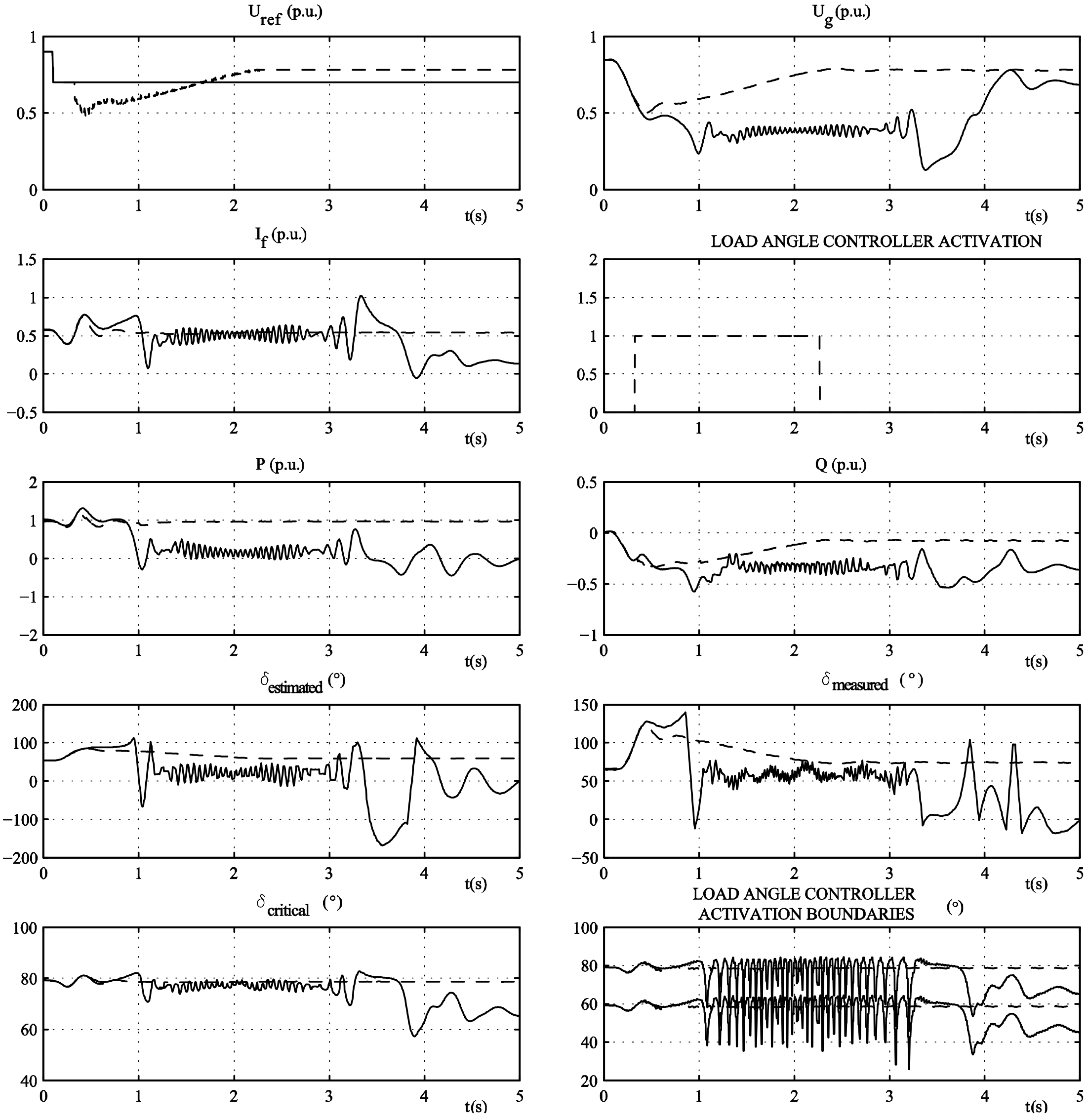

Fig. 6. Experimental responses for synchronous generator excitation control system without load angle controller (solid line) and with load angle controller (dashed line) for voltage reference value change of 0.9-0.7 p.u. and mechanical power reference of 1 p.u.

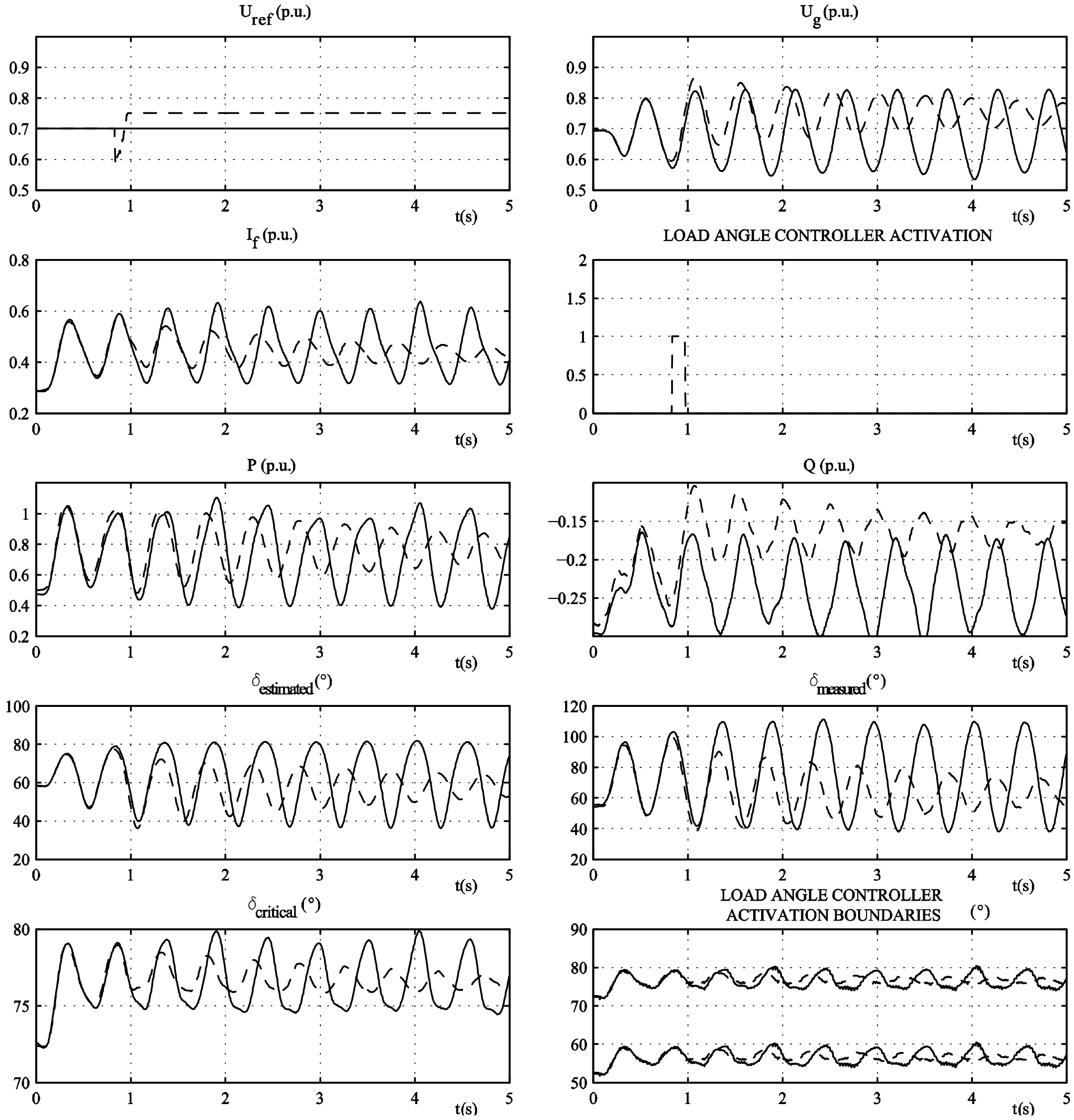

Fig. 7. Experimental responses for synchronous generator excitation control system without load angle controller (solid line) and with load angle controller (dashed line) for mechanical power reference value change of 0.5-0.8 p.u. and generator voltage reference value of 0.7 p.u.

When the voltage goes down to 0.7 p.u., the reactive power the generator takes from the network increases and the operating point moves toward the stability limit [10-14]. An experiment was conducted with a mechanical power reference value of 1 p.u.

The voltage reference value change of 0.9-0.7 p.u. with a power reference of 1 p.u. has caused oscillations of all physical variables of the generator. The frequency of active power oscillations is 17.5 Hz and of the load angle oscillations 35 Hz. The active power oscillates between 1 p.u. and -1 p.u., which shows that the generator transfers into a motor operating regime. The measured load angle also oscillates. The oscillations listed are a consequence of the asynchronous operation of the synchronous generator. During the experiment, between the 3rd and 4th second, the mechanical power was set to zero in order to avoid damage to the generator. Fig. 6 shows that in this case the load angle controller managed to bring the generator back into the stable operating area. After the load angle controller action, all physical variables are stable and do not oscillate. The experimental responses show a positive influence of the load angle action on the operation of the generator in case of a voltage reference value change which would lead the generator into an unstable area.

Also, the operation of a synchronous generator excitation control system was experimentally tested with and without a load angle controller, for a generator in the capacitive operating area with a voltage reference of 0.7 p.u. and a mechanical power reference value step change. The initial mechanical power reference value is 0.5 p.u. and after the step change it is 0.8 p.u. (Fig. 7). Figure 7 shows that the mechanical power reference value step change of 0.5-0.8 p.u. with a generator voltage reference value of 0.7 p.u. led to undamped electromechanical oscillations of the frequency of 2 Hz. The load angle swings between 40 and 110 degrees, active power between 0.4 p.u. and 1.1 p.u. and reactive power between -0.18 and -0.32 p.u. The generator is at its stability limit. The response for the excitation control system with a load angle controller shows that generator voltage increases and reactive power decreases after the load angle controller is turned on. Because the generator is in a stable area after leaving the load angle control the electromechanical oscillations are damped.

Conclusion

This paper deals with the testing of a new algorithm for the expansion of a capacitively loaded synchronous generator. The algorithm assumes that a load angle controller is built into the synchronous generator excitation control system. The task of a load angle controller is returning the generator into the stable operating area in case disturbances push the generator toward the stability limit. The load angle controller is added parallel to the voltage controller within the excitation control system. A hysteresis belt solves the issue of turning the load angle controller on and off. The upper limit of the hysteresis belt determines how close to the stability limit the generator will be allowed to operate. The lower limit of the hysteresis belt determines the point (i.e. how far it is from the stability limit) to which the load angle controller will return the generator in case it were in danger of falling out of synchronism with the network.

After the generator is distant enough from the stability limit, it is possible to bring the generator back deeper into the capacitive operating area again by setting a new operating point. The action of the load angle controller within the excitation control system was tested experimentally on a lab model.

The experiments conducted on a lab model dealt with two disturbances: the voltage reference value change and the mechanical power reference value change of the synchronous generator. The results of the experiments confirm a positive influence of the load angle controller on the operation of the generator in the area near the stability limit. Therefore, by using the suggested algorithm the stable operating area of a capacitively loaded synchronous generator can be extended up to the theoretical stability limit.

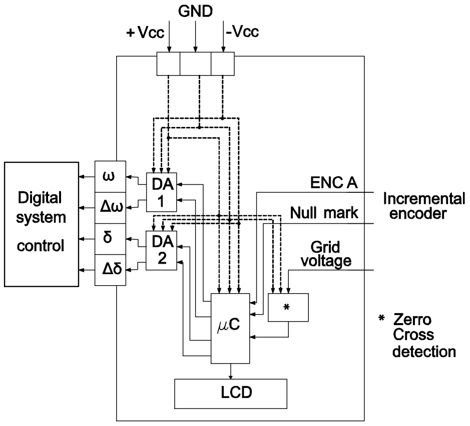

Fig. 8. Structure of device for measuring speed, speed deviation, load angle and load angle deviation

Appendix A

A.1. Appendix

The load angle was measured with an incremental encoder generating 5000 impulses per rotor rotation. It was measured at the exact moment of passing through zero of the network phase voltage, which means that for the power system frequency of 50 Hz the sampling frequency is 100 Hz. The angle was measured based on the difference between the momentary position of the rotor and the network phase voltage. Each time when passing through zero of the network phase voltage a stop was generated and the device remembered the rotor position. The rotor position was saved in the timer variable; the timer was set as an external tact counter. The counter was reset when the zero marker touched zero. The resolution of load angle measuring was in this case 0.36 degrees. The output constant of the load angle was 54.25 mV/ degree.

A.2. Appendix

The nominal data of the synchronous generator are listed below.

U_n	400 V
I_n	120 A
S_n	83 kVA
f_n	50 Hz
ω_n	600 rpm
$cos\varphi_n$	0.8
U_{fn}	100 V
I_{fn}	11.8 A
X_d	0.8 p.u.
X_q	0.59 p.u.
X_e	0.2 p.u.

A.3. Appendix

Load angle controller settings:

K_p	3
K_i	1

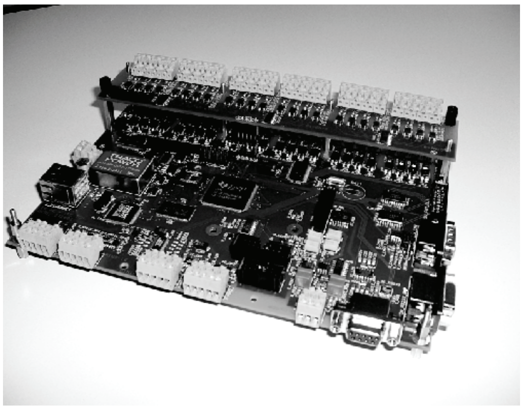

Fig. 9. Digital control system board

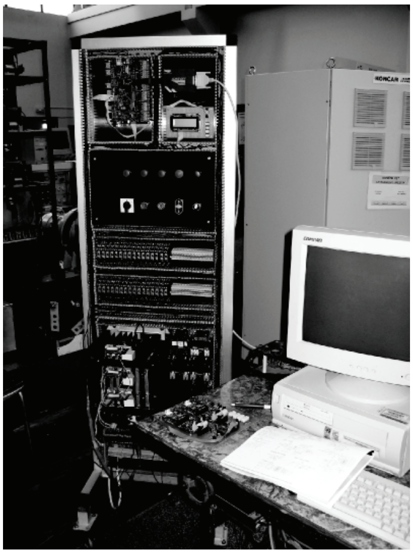

Fig. 10. Experimental setup

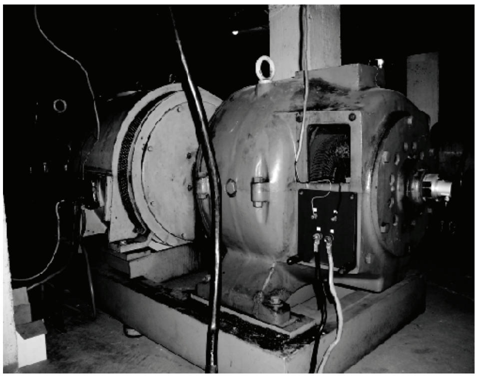

Fig. 11.Synchronous generator with DC drive motors

A.4. Appendix

The laboratory model on which the experiments were conducted is shown in Fig. 9, Fig. 10, and Fig. 11. It consists of a synchronous generator (Fig. 11), which is connected to a power system through reactances. The control system based on a DSP TMS320F2812 digital system is shown in Fig. 9 and Fig. 10.

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