A FAST FOLLOWING SYNCHRONIZER OF GENERATORS

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ABSTRACT

This paper presents the theory and the implementation of a new type synchronizer of generators, the Fast Following Synchronizer, which is implemented by closed-loop control systems in which the motive power and the excitation current of a generator are controlled quickly and accurately so as to make the amplitude, frequency and phase-angle of the generator voltage follow those of the bus voltage of the power system which the generator is going to be switched in. Thus, the voltage across the generator breaker can be kept at zero continuously and the generator can be switched in at any time without any surge current.

SYMBOLS

G---- generator,
GB---- generator breaker,
Ug---- generator voltage,
Vg---- amplitude of the generator voltage,
f_g---- frequency of the generator voltage,
δg---- phase-angle of the generator voltage,
Us---- power system voltage,
Vs---- amplitude of the power system voltage,
fs---- frequency of the power system voltage,
δs---- phase-angle of the power system voltage,
ΔU---- amplitude difference between the two voltages, =Vg-Vs,
Δf---- frequency difference between the two voltages, =fg-fs,
$\Delta\delta$---- phase-angle difference between the two voltages, $=\delta g-\delta s$,
1PT---- terminal potential transformer,
2PT---- bus potential transformer,
ωg---- angular speed of the generator voltage vector,
ωs---- angular speed of the power system voltage vector,
$\Delta\omega$---- angular speed difference between the two voltage vectors, $=\omega g-\omega s$,
bt---- transient speed droop,
Td---- time constant of the transient droop,
q_o---- no-load turbine flow rate,
Tw---- water starting time,
Tj---- inertia constant of the generator set,
Ty---- servomotor time constant,
Xg---- angular speed of the generator voltage vector, in per unit of increment, $=\Delta\omega g/\omega_r$,
Xs---- angular speed of the power system voltage vector, in per unit of increment, $=\Delta\omega s/\omega_r$,
ω_r---- base angular speed of the power system voltage vector,
Ko---- gain of phase-angle difference control,
K_1---- gain of frequency difference control,
K_2---- gain of frequency-difference differential control,
K_3---- gain of frequency-difference two-order differential control,
S---- differential operator,
ϕ---- output signal of the Fast Following Synchronizer,
Y---- servomotor displacement,
m_t---- motive torque of the hydroturbine,
m_g---- counter-torque of the hydrogenerator set,
i_x---- dead zone of the control system,
Δn---- peak value of the governor speed error,
n_e---- rated turbine speed,
U_B---- base voltage of the control system, the output voltage of the frequency measurement circuit with the frequency difference deviation up to 100%,
t---- time.

INTRODUCTION

It is essential and of a great technico-economic significance from a point of view of security and stability of an electric power system for a generator to be switched in quickly and smoothly. The frequent synchronization of synchronous generators has always been emphasized.

Self-synchronization, without voltage and phase-angle conditions, is simple, quick and easy of automation. Because of the above advantages, the Automatic Self-synchronizer has been effectively used for redundant hydrogenerators to be switched in the power system in some fault conditions. But its application gets more and more restricted because of the large surge current.

To switch a generator in the power system quickly with the smallest surge current, the ideal conditions of the Quasi-synchronization are $\Delta U=0$, $\Delta f=0$ and $\Delta\delta=0$, where ΔU, Δf and $\Delta\delta$ are the amplitude difference, the frequency difference and the phase-angle difference between the generator voltage and the power system voltage respectively. In fact, however, the Automatic Quasi-synchronizer up to now, is very difficult to meet all the above ideal conditions simultaneously. In general, the conventional Automatic Quasi-synchronizer has following characteristics.

1. It is an automatic device of mono-purpose utilization, of which the hardware is independent of that of the governor system and the excitation system of the generator.
2. It controls the frequency and the amplitude of the generator voltage discontinuously. So it can not exactly in principle make the generator breaker to be switched in at the very moment of $\Delta f=0$.
3. It only observes the phase-angle difference between the generator and the system voltages. As $\Delta\delta$ is uncontrollable, the moment when the two voltages are momentarily in phase has to be captured. It is difficult to find accurate extrapolation time for the generator breaker to be switched on at the very moment of $\Delta\delta=0$.
4. It is rather slowly to finish the synchronization of a generator by the Automatic Quasi-synchronizer.

The above analysis reveals the problems of the theory and the implementation of the present Automatic Self-

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synchronizer and Automatic Quasi-synchronizer. This paper presents a new type synchronizer, the Fast Following Synchronizer, which combines the advantage of the fast speed of the Automatic Self-Synchronizer with that of the small surge current of the Automatic Quasi-synchronizer.

FAST FOLLOWING SYNCHRONIZER

Fig. 1 shows the general layout of the Fast Following Synchronization which has the following characteristics.

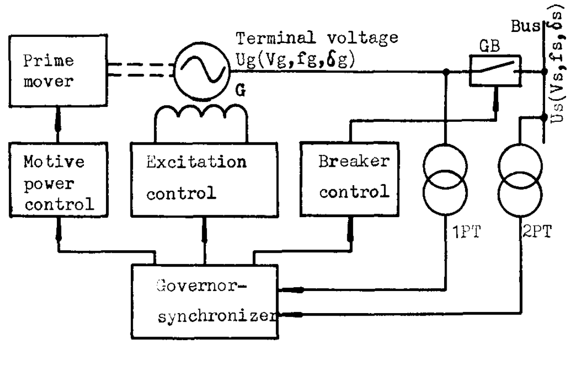

Fig. 1. The general layout of the Fast Following Synchronization.

1. The Fast Following Synchronizer is implemented by a closed-loop control system in which the input signals are the synchronizing generator and the power system voltages, ΔU, Δf and $\Delta\delta$ are measured, the motive power(steam flow of the steamturbine or water flow of the hydroturbine)and the excitation current of the generator are controlled so as to make the amplitude, frequency, and phase-angle of the generator voltage follow those of the bus voltage of the power system which the generator is going to be switched in. Thus the voltage across the generator breaker can be kept at zero continuously before the generator switched in. The switching-in signal, therefore, can be sent out at any time smoothly without any surge current.

2. The Fast Following Synchronizer is the extension of the microcomputer electrical-hydraulic governor and without special hardwares. It is named "The Governor-synchronizer", which makes the generator voltage follow the bus voltage of the power system by executing the program of the following synchronization control before the generator switched in, sends out switching-in signal according to the conditions of quasi-synchronization,and executes the program of governing control, functioning as a governor after the generator switched in.

SPECIFICATION OF CONTROL SYSTEM DESIGN

The dynamic behaviour of a generator on no-load has no effect on the power system. The Fast Following Synchronizer aims at switching the generator in the power system as quickly and smoothly as possible. The design goals for the Fast Following Synchronizer are given below.

1. The Fast Following Synchronizer should make the amplitude, frequency and phase-angle of the generator voltage follow those of the bus voltage of the power system accurately with $\Delta U=0$, $\Delta\omega=0$ and $\Delta\delta=0$.

2. The control system must be stable with a satisfactory margin of stability, irrespective of some disturbances.

3. The control system should be responsive, as it is vitally important for a generator to be switched in the power system as quickly as possible.

THE IMPLEMENTATION OF THE FAST FOLLOWING SYNCHRONIZER

Modern excitation control makes the amplitude of the generator voltage fairly easier to follow that of the bus voltage. More critical conditions are the other two synchronization ones of $\Delta f=0$ and $\Delta\delta=0$, that is, the frequency and phase-angle of the generator voltage following those of the bus voltage of the power system accurately, which is made difficult by the complicated structure of the modern governor, the non-linear backlash and the water(steam)inertia. Once the Fast Following Synchronization control succeeds, only the problem of sending out switching-in signal is left. This paper will describe the implementation of the frequency following and the phase-angle following, based on a hydrogenerator set on which the field test was conducted.

Mathematical Model of Control System

The field test was conducted on the No. 3 hydrogenerator set at a hydropower station in the Hubei province in China. The mathematical model for the Fast Following Synchronizer studies is derived[1], and a complete transfer function block diagram of the test system is shown in Fig. 2. Several problems concerned are given below.

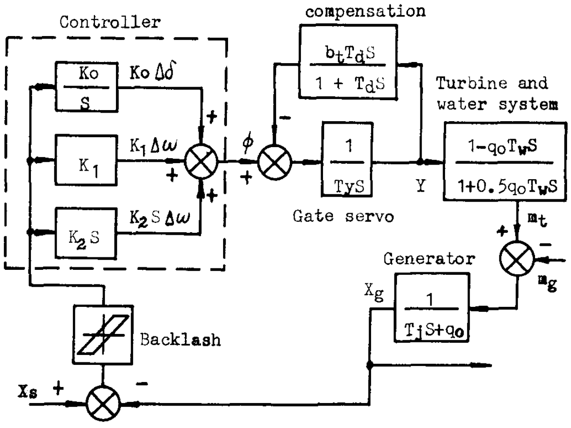

Fig. 2. The complete transfer function block diagram of the test system

1. There are various type of controllers for the Fast Following Synchronizer. A proportional plus derivative plus two-order derivative controller over $\Delta\delta$ is used here. The output of the controller is given by

$$\begin{aligned}\phi &= K_o\Delta\delta + K_1\frac{d\Delta\delta}{dt} + K_2\frac{d^2\Delta\delta}{dt^2}\\ &= K_o\Delta\delta + K_1\Delta\omega + K_2\frac{d\Delta\omega}{dt}\\ &= K_o\int\Delta\omega\, dt + K_1\Delta\omega + K_2\frac{d\Delta\omega}{dt}\end{aligned} \quad (1)$$

Obviously, it can be considered as a proportional-integral-derivative controller over $\Delta\omega$.

2. The complete system model is developed with the consideration of the water impact effect, because the water inertia has a significant effect on the sys-

tem performance.

3. The parameters of an idealized turbine are used in the modelling of the turbine because the practical parameters are not obtained yet.

4. The electrical-hydraulic governor consists of the mechanical-hydraulic transducers and the displacement feedback component as well as the electrical unit. The friction and backlash between the mechanical component parts result in the non-linear characteristic of the governor, which affects the control system performance notably and is characterized by the dead zone i_x of the governor system:

$$i_x = \frac{\Delta n}{n_e} \times 100\% \qquad (2)$$

where, Δn is the peak value of the governor speed error and n_e is the base speed of the generator.

Dynamic Behaviour Analysis

The performance of the control system is examined by both analogue computation and dynamic simulator tests as the analytical methods are not always suitable for studing the dynamic behaviour of the system with nonlinearality.

The Fast Following Synchronizer is used for a generator in no-load state to be switched in the power system. The mechanical damping torque of the generator, therefore, is negligibly small, i.e. mg=0.

The results of dynamic behaviour analysis are obtained using an analog computer. The responses of the system to a step input are shown in Figs. 3-7.

1. The water inertia of the turbine-penstock worsens the performance of the control system(Fig. 3.).

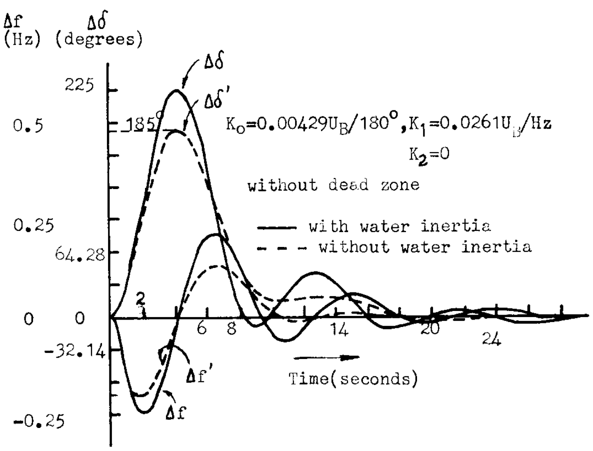

Fig. 3. The effect of the water inertia on the system performance.

2. The backlash in the governor worsens the system performance evidently. It not only increases the amount of overshoot and lengthens the settling time but also results in the limit loop in the control system(Fig. 4.)

3. A derivative control over the frequency difference(acceleration feedback of the generator set) remarkably improves the dynamic performance of the system. Fig. 5 shows the effect of the derivative control on the system performance when the backlash of the governor is neglected. Fig. 6 shows that with consideration of the backlash of the governor, the derivative control can restrain the limit loop effectively in this case.

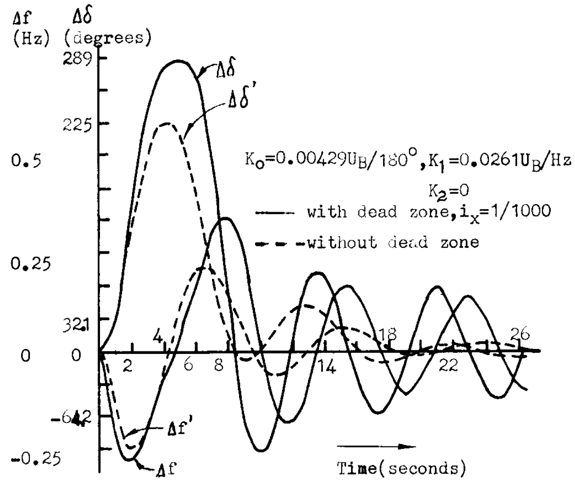

Fig. 4. The effect of the backlash on the system performance.

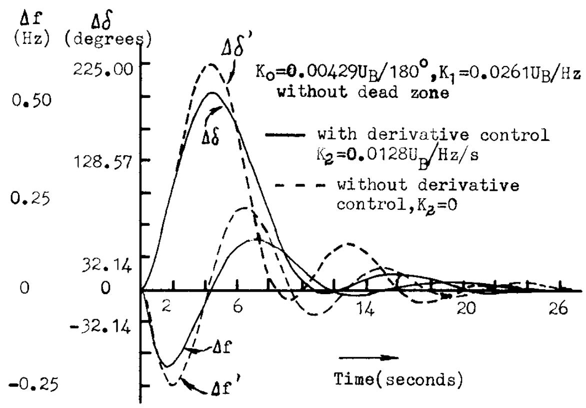

Fig. 5. The effect of the derivative control on the system performance.

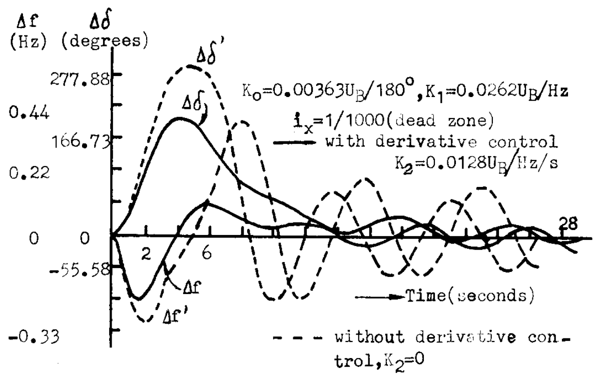

Fig. 6. Response of the system to a step input, showing the limit loop restrained by a derivative control.

The analog computation also shows that the limit loop can be restrained on condition that the dead zone is relatively small($i_x \leqslant 2/1000$)and when the control gains Ko--K_2 are properly chosen.

4. The synchronizer output including a two-order derivative control over $\Delta\omega$ can be written as,

$$\phi = K_o\Delta\delta + K_1\Delta\omega + K_2\frac{d\Delta\omega}{dt} + K_3\frac{d^2\Delta\omega}{dt^2} \qquad (3)$$

The system performance can be made even better with a two-order derivative control over $\Delta\omega$. Fig. 7 shows that the limit loop can be eliminated, the amount of overshoot is decreased and the control time is shortened.

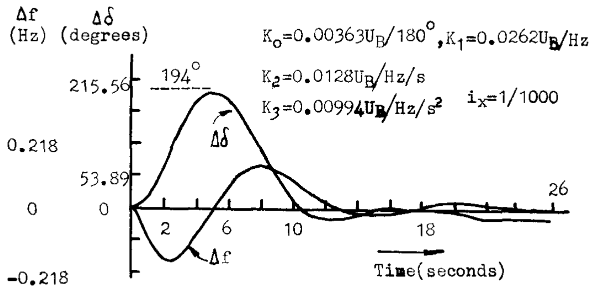

Fig. 7. The effect of the two-order derivative control on the system performance.

Correspondence between the simulator test results and analog computation results gives preliminary proof of correctness of the mathematical model of the control system. The simulator test results are not given in this paper.

The Field Test Results

1. Testing Sets:

a. Turbine
- Power Capacity 9260 KW
- Base Speed 187.5 r.p.m.
- Designed Water Head 18.5 m
- Testing Water Head 23 m
- Flywheel Moment GD^2=496 T.m^2

b. Generator
- Base Power 8800 KW
- Base Voltage 6300 V
- Base Current 1010 A

c. Governor
- Type JST-100(mechanical-hydraulic governor)

2. Test Results

The Fast Following Synchronizer was tested on the No. 3 hydrogenerator set at a hydropower station in the Hubei province in China. The frequency of the generator voltage is kept at first at 49Hz or 51Hz by the electrical-hydraulic JST-100 governor, and then to observe how the Fast Following Synchronizer makes the frequency and phase-angle of the generator voltage follow those of the bus voltage of the power system. The test results are shown in Fig. 8 and Fig. 9.

Fig. 8 and Fig. 9 show that the Fast Following Synchronizer takes 16 seconds for the frequency and phase-angle of the generator voltage to enter and remain in the state of following those of the bus voltage of the power system,without limit loop. The generator breaker,therefore,can be switched on at any time without any surge current.

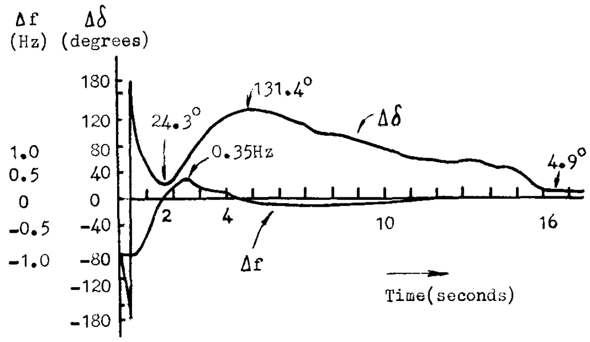

Fig. 8. The process of fg changing from 49Hz to f_s

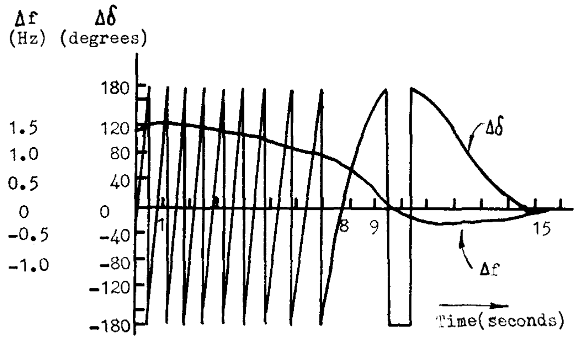

Fig. 9. The process of fg changing from 51Hz to f_s

CONCLUSIONS

From the above theoretical investigations and test results,the following points are concluded.

1. Based on the electrical-hydraulic governor and the modern excitation regulator,microcomputer control can make the amplitude,frequency and phase-angle of the generator voltage follow those of the bus voltage of the power system which the generator is going to be switched in. Thus,Δf,$\Delta\delta$,andΔU can be quickly controlled so as to be kept at zero continuously before the generator switched in. The generator,therefore,can be switched in the power system quickly and smoothly without any surge current,this is of great significance especially in system fault conditions.

2. The accurate measurement of the frequency and phase-angle and the good performance of the mechanical-hydraulic transducers are necessary for the phase-angle control of high accuracy. By introducing the derivative control and the two-order derivative control over the frequency difference into the Fast Following Synchronizer and with the control gains(Ko,K_1,$K_2$and K_3)properly chosen,an electrical-hydraulic governor with a dead zone of $i_x \leqslant 0.2\%$ doesn't give rise to the limit loop in the control system,and even the poor performance of a governor system can be remarkably improved.

3. Although the analysis and test results described in this paper are based on a hydrogenerator set, it can be affirmable easier to implement the Fast Following Synchronizer on steam turbo-generators,because the governor of which is far more sensitive than that of hydrogenerators.

4. The Fast Following Synchronizer shares the same hardware with the microcomputer electrical-hydraulic governor. Automatic devices in power stations are economized by the multi-purpose utilization of the microcomputer.

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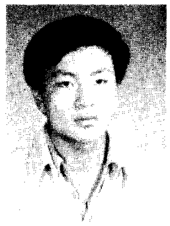

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