Two Methods of Resynchronization Control in Power System

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Each generator in a power system has its own transient stability margin. Usually, the generator which is over the stability region and falls out of the synchronous state, is separated from the power system in order to have no influence on the other system. However, it is known that under certain conditions such a generator is able to return to the synchronous state after the asynchronous operations. This paper presents the two resynchronization control methods which make the generator fallen out of pace return to the synchronous state. These methods are mainly based on the suboptimal control and some sophisticated methods using the linear optimal regulator. It is also the purpose of this paper that the linear optimal regulator is applicable to the problem in which the system equations are nonlinear.

1. Introduction

Concerning rotor oscillations of the generator following a transient disturbance, the first swing is most crucial, and the critical reclosing time that permits the machine to remain in a stable region is uniformly determined by the equal-area criterion in a one-machine infinite-bus system[1)]. When the area in acceleration exceeds that in deceleration, the machine is reaccelerated, finally falling out of pace. And, generally, it is necessary to separate the generator which fell out of pace from the power system. Separation of the generator is not, however, desirable in view of the reliability of the power supply, because of a sizable time needed to reclose the generator which has once separated from the system. With respect to this problem, the resynchronization phenomena which result in synchronizing state after the asynchronous operations have been considered in some literature[2)]. But, this sort of problems have not been so much investigated.

In this paper we propose two resynchronization control methods which lead the generator from any asynchronous state to the synchronous state, without the separation of the generator from the power system. The dynamic equations of the generator in a transient period are described by the nonlinear differential equations with the sinusoidal function.

The schemes of the resynchronization control are constructed by the combination of the linear optimal generators and some sophisticated methods based on the presence of the equilibrium stable point in every 2π period and the periodicity of the sinusoidal function.

The effectiveness of those methods is shown by the simulation in a one-machine infinite-bus model system.

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2. Resynchronization Control

2.1 Resynchronization control using series capacitor and series resistor

Consider a one-machine infinite-bus system with the series capacitor and the series resistor as shown in Fig. 1[5]. Denoting the generator voltage back of transient reactance by E_1, the infinite bus voltage by E_2 and the system reactance as viewed from E_1 by X, the generator output power P_{e1} is given by

$$P_{e1} = \frac{E_1 E_2}{X} \sin \delta, \tag{1}$$

where δ is the phase angle between E_1 *and* E_2. On the other hand, when the series capacitor and the series resistor are inserted, the voltage and current vector diagram of this system is shown in Fig. 2.

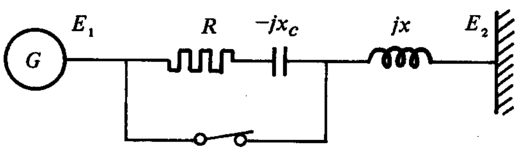

Fig. 1. One-machine infinite-bus model system

Regarding the infinite bus voltage E_2 as a base vector, the output power P_{e2} is as follows:

$$\dot{E}_2 = E_2 \angle 0, \quad \dot{E}_1 = E_1 \angle \delta, \tag{2}$$

$$R - j(X_c - X) = Z \angle -\theta, \tag{3}$$

$$\begin{aligned} P_{e2} &= R_e(\bar{\dot{E}}_1 \dot{I}_1) = R_e\left(\bar{\dot{E}}_1 \frac{\dot{E}_1 - \dot{E}_2}{R - j(X_c - X)}\right) \\ &= R_e\left(E_1 \angle -\delta \cdot \frac{E_1 \angle \delta - E_2 \angle 0}{Z \angle -\theta}\right) \\ &= \frac{E_1^2}{Z} \cos\theta - \frac{E_1 E_2}{Z} \cos(-\delta + \theta). \end{aligned} \tag{4}$$

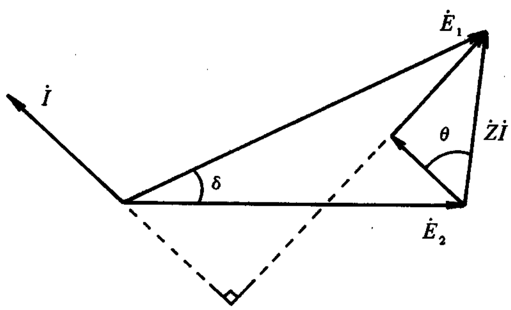

Fig. 2. Vector diagram

If the series resistance and series capacitance are chosen so that the power-angle curve given by Eq. (4) crosses the power-angle curve given by Eq. (1) at $\delta = \delta_c$ in Fig. 3, then the output power to absorb the excess energy increases as shown below.

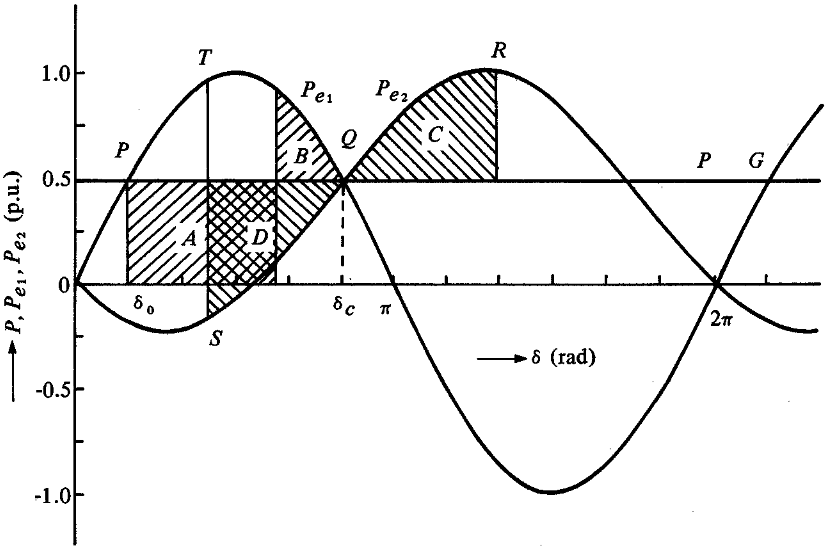

Fig. 3. Power-angle characteristic curves

When the accelerating energy as given by area A in Fig. 3 exceeds the decelerating energy as given by area B, the generator usually falls into instability. If the series capacitor and the series resistor are switched on simultaneously at point Q in Fig. 3, then the generator continues to be decelerated and the phase angle continues to increase up to point R where $A = B + C$. After the generator has reached point R, it moves along the curve R–Q–S and the phase angle swings up to point S where $C = D$. If both the series capacitor and the series resistor are switched off at point S, then the operating point moves to point T. Thereafter, the generator continues to swing stably.

When the initial accelerating energy is more large and the phase angle δ continues to increase, the power angle curves are connected at point G. By repeating the same procedures, the excess energy is absorbed and the generator finally comes to the state of oscillation around one of the equilibrium points.

Next, we propose a method to suppress the subsequent power swings by the control of series capacitor. Regarding the series capacitance $-ju$ inserted into the transmission line as a control variable, the generator output power P_e is represented by

$$P_e = \frac{E_1 E_2}{X - U} \sin \delta . \tag{5}$$

The swing equation is represented by

$$M \frac{d^2\delta}{dt^2} = P - P_e. \tag{6}$$

Regarding δ and $\dot{\delta}$ as the state variables, let $X_1 = \delta$ and $X_2 = \dot{\delta}$. Then we obtain

$$\dot{X}_1 = X_2 ,$$
$$\dot{X}_2 = \frac{1}{M}(P - \frac{E_1 E_2}{X-U} \sin X_1). \tag{7}$$

Assuming that the mechanical impput power P is constant and linearizing Eq. (7) around $u = 0$, we get

$$x = Ax + Bu, \tag{8}$$

where $x = X - X_0$, X_0 is the stable equilibrium point and

$$A = \begin{bmatrix} 0 & 1 \\ a_{21} & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ b_2 \end{bmatrix},$$

$$a_{21} = \frac{E_1 E_2}{X} \cos X_{10} , \quad b_2 = \frac{E_1 E_2}{X} \sin X_{10}.$$

The quadratic form evaluation is defined by

$$I = \int_0^\infty (x'Qx + ru^2) dt , \tag{9}$$

where Q is a positive-definite symmetric weighting coefficient matrix for the state variable, and r is a positive-definite weighting coefficient.

The optimal solution for Eqs. (8) and (9) can be obtained analytically. The optimal control for the above problem is given by

$$u^* = - \frac{1}{r} B'Kx, \tag{10}$$

where K is a positive-definite matrix solution of the following Riccati-equation:

$$- KBr^{-1}B'K + A'K + KA + Q = 0. \tag{11}$$

Finally, by combining the above two procedures we obtain the resynchronization control scheme illustrated in Fig. 4.

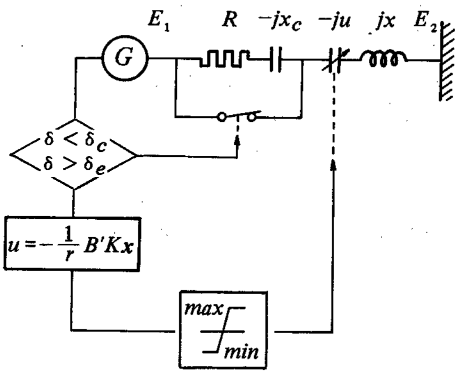

Fig. 4. Schematic diagram of resynchronization control

2.2 Resynchronization control using governor and excitation control

Consider a one-machine infinite-bus model system with a load, shown in Fig. 5[6]. In this case, the equations of the system are given as follows:

$$M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} + P_e = P, \tag{12}$$

where

$$P_e = E_I^2\, Y_{11}\, \cos\theta_{11} + E_I V Y_{12}\, \cos(\theta_{12}-\delta).$$

The next equations also exist for the excitation and governor system:

$$E_I + T_{do}\frac{dE_q'}{dt} = E_{fd}, \tag{13}$$

$$P + T_G\frac{dP}{dt} = X_p. \tag{14}$$

The relation exists between E_I and E_q':

$$E_q' = E_I - (X_d - X_d')I_d, \tag{15}$$

where

$$I_d = -E_I Y_{11}\, \sin\theta_{11} - VY_{12}\, \sin(\theta_{12} - \delta). \tag{16}$$

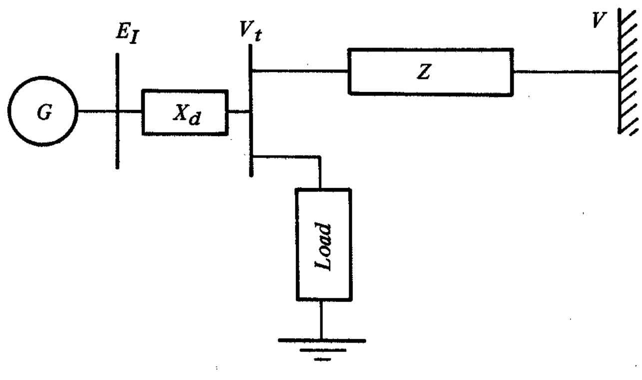

Fig. 5. One-machine infinite-bus model system

Linearizing these equations around the equilibrium state and rearranging them, we have

$$\dot{x} = A(x_0)\, x + Bu, \tag{17}$$

where

$$x = (E_I - E_{I0}, \delta - \delta_0, \delta, P - P_0)',$$

$$u = \{(E_{fd} - E_{fd0})\,/\,b_2 T_{d0}, (X_p - X_{p0})\,/\,T_G\}',$$

$$A(x_0) = \begin{bmatrix} -\dfrac{1}{T_{d0} b_2} & 0 & -\dfrac{c_2}{b_2} & 0 \\ 0 & 0 & 1 & 0 \\ -\dfrac{D}{M} & -\dfrac{c_1}{M} & -\dfrac{D}{M} & \dfrac{1}{M} \\ 0 & 0 & 0 & -\dfrac{1}{T_G} \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}',$$

$$\begin{aligned} b_1 &= 2E_I Y_{11} \cos\theta_{11} + VY_{12} \cos(\theta_{12} - \delta_0), \\ c_1 &= -E_I VY_{12} \sin(\delta_0 - \theta_{12}), \\ b_2 &= 1 + (X_d - X_d') Y_{11} \sin\theta_{11}, \\ c_2 &= -(X_d - X_d') VY_{12} \cos(\theta_{12} - \delta_0), \end{aligned}$$

E_I : open circuit voltage of the machine,
E_q' : voltage back of transient reactance,
Y_{11} : self-admittance of the network at the internal bus of the machine,
Y_{12} : mutual admittance between the internal bus and the infinite bus,
θ_{11} : argument of Y_{11},
θ_{12} : argument of Y_{12},
δ : rotor angle of the machine,
P : mechanical output of turbine,
P_e : electrical power output,
X_d : direct axis synchronous reactance,
X_d' : direct axis transient reactance,
I_d : direct axis current of the machine,
T_{d0} : time constant of open-circuit field,
T_G : time constant of turbine,
M : inertia constant of the machine,
D : damping coefficient,
E_{fd} : field voltage,
X_p : bulb position of governor.

The strong nonlinearity of the generator output narrows the effective region of the linearized Eq. (17). However, we may linearize the system equations by using two linear equations as shown in Fig. 6 :

$$\begin{aligned} \dot{x} &= A_1 x + Bu \quad (\text{around } \delta_0), \\ \dot{x} &= A_2 x + Bu \quad (\text{around } \delta_c), \end{aligned} \tag{18}$$

where A_1 and A_2 are the matrices linearized at δ_0 and δ_c, respectively.

The quadratic form evaluation is defined by

$$I = \int_0^\infty (x'Qx + u'Ru)\, dt, \tag{19}$$

where the matrices Q and R are the weighting matrices for the state vector and the control

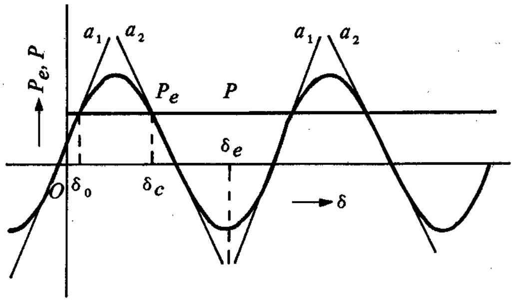

Fig. 6. Approximate power output by the linear equations

vector. The optimal controls which minimize Eq. (19) for the linearized system A_1 or A_2 are given as follows, respectively :

$$\begin{aligned} u &= -R^{-1}B'K_{A1}x \quad (\text{around } \delta_0), \\ u &= -R^{-1}B'K_{A2}x \quad (\text{around } \delta_c), \end{aligned} \tag{20}$$

where K_{A1} and K_{A2} are the matrix solutions of the following Riccati-equation for the optimal control problem in the linear system :

$$A_i'K_{Ai} + K_{Ai}A_i + Q - K_{Ai}BR^{-1}B'K_{Ai} = 0. \tag{21}$$

Using these two optimal regulator, we consider the following control system over a period of phase angle δ :

$$\begin{aligned} u &= -R^{-1}B'K_{A1}x \quad (\delta < \delta_0), \\ &= -R^{-1}B'\left(\frac{\delta_c - \delta}{\delta_c - \delta_0} K_{A1} + \frac{\delta - \delta_0}{\delta_c - \delta_0} K_{A2}\right)x \quad (\delta_0 < \delta < \delta_c), \\ &= -R^{-1}B'K_{A2}x \quad (\delta > \delta_c). \end{aligned} \tag{22}$$

In order to have the resynchronization control, we set the threshold value δ_e and propose the repetition control system as illustrated in Fig. 7.

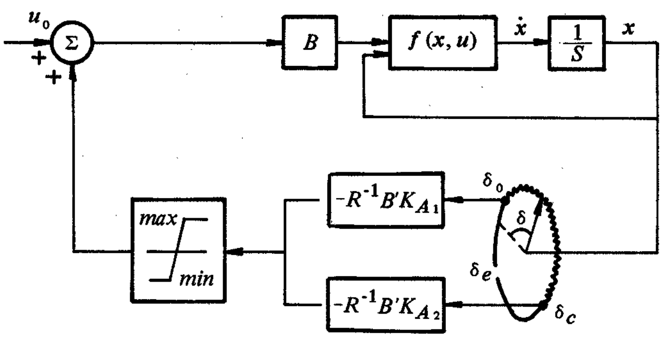

Fig. 7. Resynchronization control scheme using the combination of the optimal linear regulators

3. Numerical Examples

As the numerical example of the resynchronization control using the series capacitor and the series resistor, we assume the system parameters and the normal operating condition (the initial condition) in Fig. 4 as follows:

$$E_1 = 1.02, \quad E_2 = 1.0, \quad X = 2.5, \quad X_c = 1.758,$$
$$R = 1.0, \quad P = 0.5, \quad M = 0.04 \text{ sec}^2, \quad \delta_0 = 0.512 \text{ rad},$$
$$\delta_c = 2.618 \text{ rad},$$

where all parameters are given in per unit (p.u.).

Let the series compensation factor in the normal condition be 60 %, that is, $u_0 = -1.5$ and $-0.5 \leqq u \leqq 0.5$ for the range of the control value, and let $Q = I$ (unit matrix), $r = 1$ in Eq. (9). As the system disturbance, we assume a three phase short circuit fault near the station.

The phase diagrams for t_c = 0.48 sec, 0.64 sec and 0.72 sec are illustrated in Fig. 8, where t_c is the dead time for the dissipation of the arc. Fig. 9 is the time response curves of the phase angle δ and the control variables. It is observed that both the series capacitor X_c and the series resistor R are inserted into the line at first, then the suboptimal control by the series capacitor u follows, and the generator finally returns to the synchronous state.

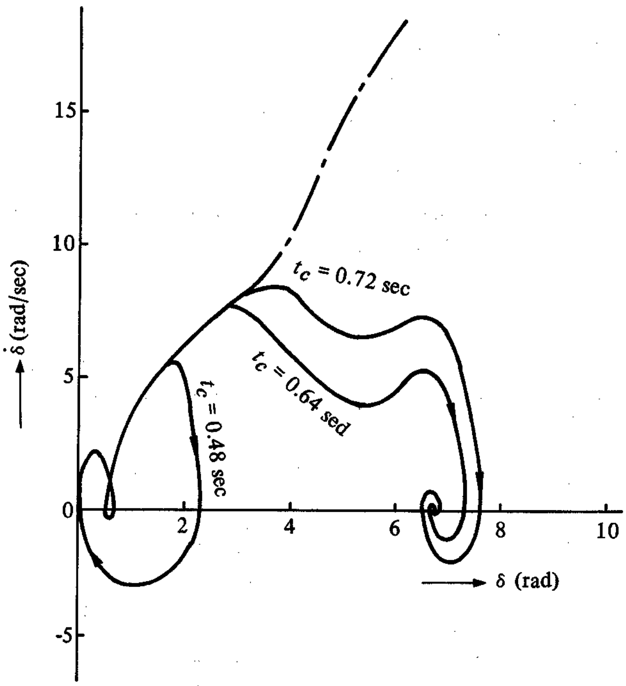

Fig. 8. Phase diagram of resynchronization phenomena

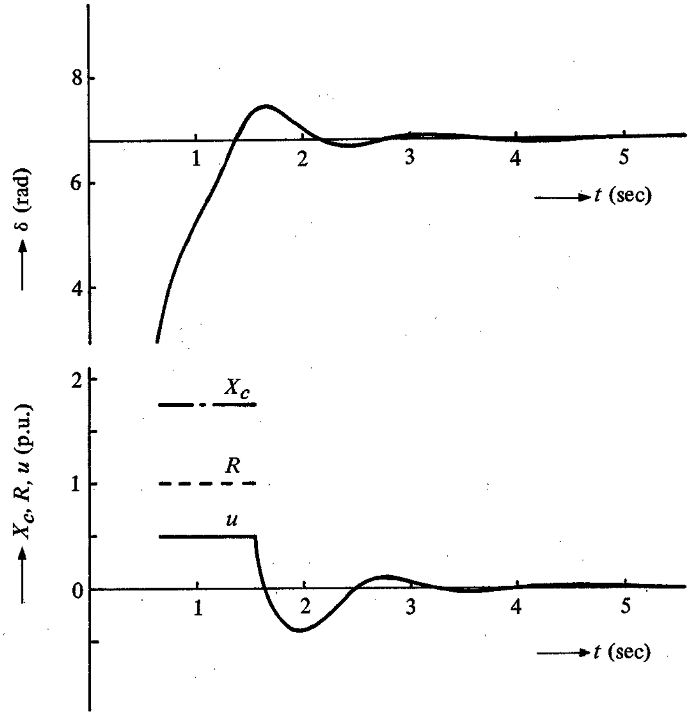

Fig. 9. Time response characteristic curves in the case of t_c = 0.64 sec

Next, we consider a case using the governor and the excitation control. Let the parameters be taken as follows :

$M = 0.06\ \mathrm{sec}^2$, $X_d = 0.320$, $X_d' = 0.084$, $D = 0.06$,

$P_0 = 1.5$, $V = 1.0$, $E_{I0} = 1.482$, $T_{d0} = 5.0$ sec,

$T_G = 0.3$ sec, $\delta_0 = 0.436$ rad, $\delta_c = 2.443$ rad, $Y_{11} = 1.533 \angle -80°$,

$Y_{12} = 1.095 \angle 80.5°$, $Q = \mathrm{diag}\,(1, 10, 25, 3)$, $R = I$,

and, for the ranges of the excitation control and the governor,

$$-2.812 \leqq u_1 \leqq 1.884,$$

$$-3.5 \leqq u_2 \leqq 0.5.$$

The phase diagram for t_c = 0.35 sec, 0.55 sec and 0.95 sec are illustrated in Fig. 10. Every state of the generator disturbed by the fault is transfered to the stable equilibrium state after the passage of appropriate periods as in the previous example.

Fig. 11 is the time response curves of the state variables and control variables. The phase angle δ for t_c = 0.55 sec closes to the stable equilibrium point after the two periods. It is observed that each operation of the control and the generator works in order to absorb the excess energy, that is, the output of the turbine P decreases abruptly and the

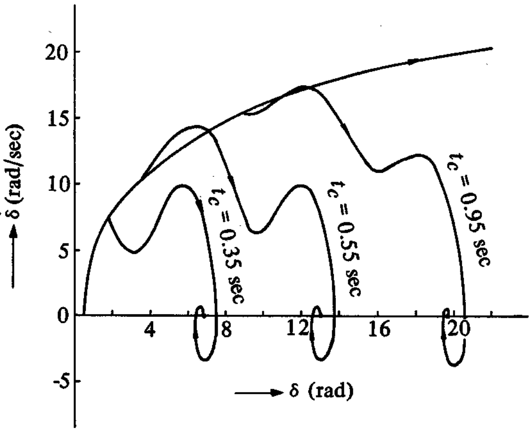

Fig. 10. Phase diagram of resynchronization phenomena

induced voltage E_I changes toward the increase of the electrical output. And, it is noted that the controls u_1 and u_2 are of Bang-Bang type at the beginning time, whereas the cost function is sellected by the quadratic form. It must be also noted that the control u_1 and u_2 are reversely operative, that is, when the control u_1 is the maximum, the control u_2 is the minimum, and vice versa.

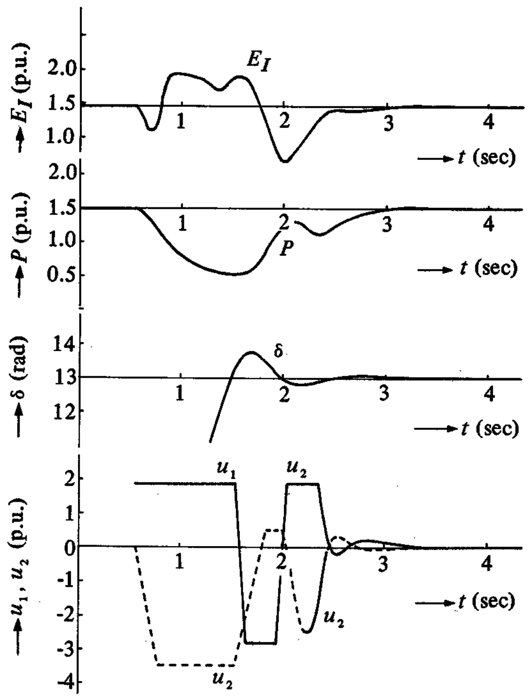

Fig. 11. Time response characteristic curves in the case of t_c = 0.55 sec

4. Discussion

First, we discuss about the method of resynchronization control using the series capacitor and the series resistor. Generally, the instantaneous connection of the series capacitor or the series resistor is danger because a large torque may be exerted on the rotor axis. In the method proposed above, the generator output varies continuously when the series capacitor and the series resistor are switched on simultaneously at point Q. Therefore the generator torque does not vary abruptly at point Q.

Although it is necessary to vary the series capacitor with time to realize the suboptimal control, it is not difficult to demonstrate that the discrete control of series capacitance is as effective as the continuous control if the series capacitor is switched at a suitable number of steps[5].

In order to realize the negative value of control, usually, we have to use a series reactor. In practice, however, we need not use the reactor if the given line is series-compensated in advance; in such a case, the effect of the series reactance is realized by reducing the series capacitance (or by switching off a part of the series capacitors).

In this paper, we consider the real power only, but in fact, the required rating of series resistor R and series capacitor X_c is considerably large although it should be of short-term rating. In this respect the proposed R-X_c control scheme has an economical drawback. The suboptimal control proposed here, however, could be realized economically because it can be realized only by switching the series capacitor of the series-compensated line.

Next, we discuss the second method of resynchronization control using the governor and the excitation control from the view point of the conventional equal area criterion. The power-angle characteristic curves in this case are drawn in Fig. 12. In Fig. 12, when the accelerating energy A exceeds the decelerating energy B, the generator is again acceler-

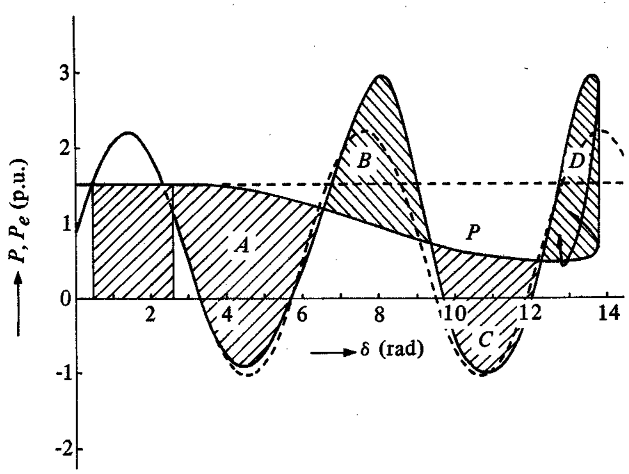

Fig. 12. Power-angle characteristic curves

ated depending on the energy C. But, the excess energy is finally compensated by the large decelerating energy D which is made by the governor and the excitation control. Then, the state of the generator moves to a new state after the two periods. It is also noted that the energy C becomes fairly small as compared with the case of no control, while the energy D becomes large.

When the initial accelerating energy A is more large, after the repetition of these processes the generator comes to one of the synchronizing states. Therefore, the requirement for the resynchronization control depends on the algebraic sum of the energy areas over one period of the phase angle.

The control system in this case would be constructed with a minor improvement of the governor and the excitor already installed in the generator. So, this method would be achieved rather easily than the former one using the series capacitor and the series resistor, and it would be more economical.

5. Conclusion

Two methods of the resynchronization control in power system have been introduced by using the nonlinearity and periodicity of the sinusoidal function included in the generator's equations. The results obtained in this paper are summarized as follows :

(1) It is theoretically confirmed that the generator fallen out of pace in power system is able to be synchronized again by the resynchronization methods proposed here.

(2) It is shown that the linear optimal regulator is applicable to the nonlinear system with some contrivance. And, it is observed that by restricting the limit of control values, the initial control gives a type of Bang-Bang one in spite of the quadratic form cost function.

(3) The methods proposed here are also economically feasible since the governor and the excitation control are already installed in the generator. In fact, there seems to be a tendency to increase of insertion of the series capacitor for the compensation.

Digital computation presented in this paper was carried out at Computer Center of University of Osaka Prefecture on the ACOS-600. This paper was partly published in Japanese in Trans. of IEE of Japan, vol. 101-B, 169 (1981).

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