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AN EFFECTIVE CONTROL STRATEGY TO ENHANCE STABILITY OF A REMOTE POWER PLANT, USING STATIC VAR COMPENSATORS

طريقة تحكم فعاله لتحسين الإستقرار لمحطة معزولة فى الشبكة باستخدام معوضات القدره غير الفعاله

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ملخص يقترح البحث طريقة للتحكم فى معوضات القدرة غير الفعاله لتحسين الإستقرار العابر وإخماد الذبذبات للمحطات المعزولة فى الشبكات الكهربية . والمعوضات المستخدمة من النوع المركب وتوضع على أطراف المولد وتتميز بأنها إقتصادية وتتكون من مكثف يوصل ويفصل ميكانيكيا (SW.C) وملف محكوم بالثيرستور مع مكثف ثابت (FC/TCR) .

تم إستنتاج طريقة للتحكم فى توصيل وفصل المكثف (SW.C) وتحديد المنحنى الأمثل لذلك على أساس تحليل منحنيات الزاوية – السرعة للمولد . بناء على الطريقة المقترحة يتم توصيل المكثف وفصله مرتين فقط وهذا كاف لإحداث الإستقرار العابر سريعا ، بل يتوقف تأرجح زاوية العضو الدوار للمولد نهائيا بعد دورة واحدة فقط .

عندما يكون المولد مستقرا فى دورة التأرجح الأولى فإن FC/TCR يعمل لإخماد الذبذبات عن طريق إشارات إضافية مثل Δ w ،Δ p . تمت المقارنة بين الإشارات الإضافية ومدى تأثيرها على إخماد الذبذبات .

يوضح البحث فعالية طريقة التحكم المقترحة وذلك بتطبيقها على نظامين كهربيين ، أحدهما بسيط والأخر يمثل جزء من الشبكة الموحدة ويتكون من ١٠ مولدات مكافئة ، ١٩ قضيب ، ١٧ حمل .

Abstract

This paper proposes a control strategy for transient stability enhancement and damping of power oscillations, using combination type SVC, connected to the machine terminals of a remote power plant. The combined type of SVC consists of a mechanically switched capacitor and a fixed capacitor/thyristor-controlled reactor.

The mechanically switched capacitor is used for augmentation of transient stability. Its switching controlis based on a phase plane analysis. The optimal switching curve is regarded to be a part of an ellipse, which is developed from examining of experimental swing curves.

The fixed capacitor/ thyristor- controlled reactor is used for damping the power oscillations. The influence of supplementary speed or power signals, in the SVC control loop on system dampimg is investigated.

Digital simulation of two systems following a three-phase fault are performed to demonstrate the effectiveness of the proposed control strategy.

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List of principal symbols

Synchronous machine variables

I_d = direct axis current
I_q = quadrature axis current
V_d = direct axis component of terminal voltage
V_q = quadrature axis component of terminal voltage
V_t = terminal voltage magnitude
E'_q = quadrature axis voltage behind transient reactance
P_e = electrical power
P_m = mechanical power
ω = machine angular velocity
δ = machine rotor angle

Synchronous machine parameters

X_d = direct axis reactance
X'_d = direct axis transient reactance
X_q = quadrature axis reactance
D = damping coefficient
T'_{do} = direct axis open circuit transient time constant
T'_{qo} = quadrature axis open circuit transient time constant
H = inertia constant (MWs/MVA)
M = $2H/(\omega_o)$
ω_o = rated frequency (rad/s)

Control system variables

V_{ref} = FC/TCR reference voltage
V_s = FC/TCR stabilising voltage
I_{Bd} = direct axis current of FC/TCR
I_{Bq} = quadrature axis current of FC/TCR

Control system parameters

T_T = delay time of thyristor circuit
K_T = gain of thyristor circuit
B_C = admittance of fixed capacitor (FC)
B_L = controlable admittance of thyristor controlled-reactor (TCR)

1. INTRODUCTION

Thyristor controlled static VAR compensators are used in transmission system applications [1,2,3,4]. It can be used to regulate system voltage, improve transmission capacity, enhance system stability and to damp power system oscillations .

The operation of SVC is inherently fast and with appropriate control, they can have a large effect on system conditions within fractions of a cycle of the normal rotor oscillations [5].

The remote systems tend to be poorly damped, and their high series impedance means that control on alternator exciters may be relatively ineffective. Thus, any improvement in damping is required, and it can be acheived by SVC [7].

Many different SVC configurations are possible. The choice of a configuration depends on a number of factors: reactive power requirements, loss characteristics, harmonic generation and cost [1] One of SVC configurations is the fixed capacitor/thyristor-controlled reactor (FC/TCR) with mechanically switched capacitor (SW.C), which is called combined type of SVC [8].

For any SVC scheme, the firing angle control of the thyristor banks determines the equivalent shunt admittance presented to the power system. The input signals to the SVC controller are the bus voltage changes and auxilliary signals at the voltage controlled bus of the system

This paper presents a control strategy for both transient stability enhancement and damping the system oscillations for a remote power plant. The first step in the proposed control strategy is the switching control of the mechanically switched capacitor for transient stability augmentation. Switch curve for SW.C insertion is an ellipse which is developed from the examination of experimental swing curves. The second step of the control strategy is the operation of FC/TCR of the SVC with supplementary speed or power signals to damp the system oscillations.

2. MATHEMATICAL MODEL

The system considerd is a remote power plant connected to an infinite bus through a double circuit transmission as shown in Fig.1. The synchronous generator of the remote power plant is described in fourth-order nonlinear mathematical model [6].

$$\dot{\delta} = \omega - \omega_o \tag{1}$$

$$M \dot{\omega} = P_m - P_e - D \omega \tag{2}$$

$$T'_{do} \dot{E}'_q = E_{fd} - E'_q - (X_d - X'_d) I_d \tag{3}$$

$$T'_{qo} \dot{E}'_d = - E'_d + (X_q - X'_d) I_q \tag{4}$$

A combination type SVC is used in the study and it is illustrated in Fig.2 [8]. The MSC bank is switched only for transient stability augmentation due to large disturbances such as, a ground fault of the transmission line. The FC/TCR part works for power system oscillations or works for a small amplitude voltage fluctuations. Equations of FC/TCR part are obtained as follows:

$$V_d = L_B I_{Bd} + \omega L_B I_{Bq} \quad (5)$$

$$V_q = L_B I_{Bq} - \omega L_B I_{Bd} \quad (6)$$

$$I_d = I_{td} + I_{Bd} \quad (7)$$

$$I_q = I_{tq} + I_{Bq} \quad (8)$$

where $L_B = X_T - \frac{1}{B_C + B_L}$

X_T is the reactance of step-down transformer T_{r3}.

3. DESCRIPTION OF THE CONTROL STRATEGY

3.1 Control of Mechanically Switched Capacitor

When the system, shown in Fig.1 is subjected to a three-phase fault on the transmission system, oscillation of generator rotor angle and speed occurs. The typical swing curves are shown in Fig.3. From the well-known curves a feature of the curves can be used for switching control.

For a remote power plant, the inter-damping is quite small, therefore, the oscillation in Fig.3 has a long duration time and it can be approximated as a sinusoidal wave as follows:

$$\omega = b \sin(t)$$
$$\delta = a \cos(t) \quad (9)$$

Equation (9) represents a typical ellipse equation, a is the length of the semi-major axis, and b is the length of the semi-minor axis. The $\omega - \delta$ curve, shown in Fig.3 can be approximately viewed as a set of ellipses with the same centre. Specified ellipse can be expressed by the following equation

$$\frac{(\delta-\delta_o)^2}{a^2} + \frac{(\omega-\omega_o)^2}{b^2} = 1 \quad (10)$$

The set of ellipses has different values of a,b, the same centre (δ_o,ω_o) and has the same ratio ($\mu = b/a$).

When the SW.C is inserted to the power system, the operating point changes and the corresponding swing curve changes also. As shown in Fig.4, the new operating point is δ_n and the corresponding swing curves are moved to the left. Examining the set of ellipses of centre δ_n, there is only one ellipse (optimal ellipse) which passes through the pre-fault operating point δ_o.

If the SW.C is switched off exactly at the pre-fault operating point δ_o, when the trajectory moves to δ_o along the optimal ellipse, the whole system will return to steady-state immediately.

3.2 Control of FC/TCR

A stabilizing controller for the FC/TCR compensator is always necessary in order to provide the required damping torque to damp power oscillations in an effective manner. A static compensator with only a voltage regulator cannot fulfill this requirement [1,8].

The block diagram of the control scheme employed in the FC/TCR compensator is shown in Fig.2. By adjusting the firing angles of thyristors TH1 and TH2 according to the variations in terminal voltage V_t and speed deviation of the generator $\Delta\omega$ or power signal ΔP, the susceptance of the inductor B_L can be regulated in a way shown in Fig.2. The mathematical equations corresponding to Fig.2 are

$$K_T\ (\Delta V_{REF} - \Delta V_t + \Delta V_S) = \Delta B_L + T_T\ \Delta \dot{B}_L$$
$$B_L = B_{L0} + \Delta B_L \qquad (11)$$

T_T and K_T represent the delay time and gain of the thyristor circuits. SVC control loop is very fast as compared to system swing oscillations. Therefore the nonlinear model of SVC can be approximated to linear model for the purpose of this analysis.

4. PROCEDURE FOR APPLICATION OF THE CONTROL STRATEGY

The control procedure involved in enhancement the transient stability and damping of the power oscillations is given in the following:

Step 1: The SW.C is switched on at fault clearing by the line protection. When $\Delta\delta$ starts being negative, the SW.C is switched off. The trajectory of (first) insertion is AB as shown in Fig.6. The AB trajectory is a portion of swing curve corresponding to the power system configuration (after clearing the fault) with inserted SW.C

Step 2: The second insertion of MSC is when the trajectory arrives at point C which belongs to the optimal ellipse. Then, switching off at point O.

Step 3: The power oscillations are damped using the FC/TCR compensator. The stabilizing control signal is the generator speed deviation $\Delta\omega$ or power deviation signal.

5. SIMULATION RESULTS

The proposed control strategy is applied to the following power systems:

1. The remote power plant connected to an infinite bus through a double circuit long transmission line, as shown in Fig.1. Its data are given in Appendix. The disturbance initiating transients is a three-phase fault occuring near the remote generator at the end of transmission line. The fault is cleared in 0.14 s by opening one of the double circuits.

The digital time simulation shown in Fig.5 depicts generator rotor angle δ, speed ω, terminal voltage ΔV_t and power P without SVC. Fig.5 shows also the same variables when a SW.C of 0.25 pu rating is employed.

Without SW.C the system is unstable. With SW.C, the transient stability can be augumented in a rapid manner. The δ-ω trajectory is shown in Fig.6.

For determination the optimal ellipse equation, the following results are requried:

$$\delta_o = 48.14^\circ = 0.840 \text{ rad}$$

$$\delta_a = 27.20^\circ = 0.475$$

$$a = \delta_o - \delta_a = 0.365 \text{ rad.}$$

$$\mu = 0.022$$

$$b = \mu\, a = 0.008$$

Substituting in eqn.(10), the optimal ellipse equation is

$$\frac{(\delta - 0.840)^2}{(0.365)^2} + \frac{(\omega - 1.0)^2}{(0.008)^2} = 1 \qquad (12)$$

Fig.7 shows the generator rotor oscillations, due to the above disturbance but with duration of 0.12 sec. Curve (a) corresponds to the case without control. Curve (b) and curve(c) correspond to the use of speed and power deviation feedback signals in the loop of FC/TCR compensator,respectivilly. It is noted that the use of FC/TCR compensator enhances the damping of rotor oscillations. The best rotor angle damping is obtained when using power signal in the control loop.

For the above fault with duration of 0.14 sec, the response of rotor angle is obtained, as shown in Fig.8. Without control,the system is unstabile (curve a). With SW.C only, the system is stable in the first swing and the subsequent rotor angle oscillations are greatly damped (curve b). The oscillations are totally stopped in 1.0 period of oscillation of rotor angle, when SW.C and FC/TCR are applied together to the system (curve c).

2. The 10-generator,19-bus power system described in [9]. Fig.9 illustrates the network configuration.The machine and network data are given in Appendix. Generator No.1 represents the remote power plant. Three-phase fault near generator No.1 of 0.40 s is investigated.The generator rotor angles and speeds are represented in COA reference frame as follows:

$$\theta_i = \delta_i - \delta_o \tag{13}$$

$$\omega_i = \omega_i - \omega_o \tag{14}$$

where
$$\delta_o = \sum_1^n \delta_i M_i / M_T$$

$$\omega_o = \sum_1^n \omega_i M_i / M_T$$

where M_i is the inertia constant of generator i and M_T is defined by

$$M_T = \sum_1^n M_i$$

The generator rotor angles θi responses are shown in Fig.10. For the above disturbance, generator No.1 runs out of step firstly and thus it is responsible for the first swing instability.

Fig.11 shows the effect of using SVC on the system response. MSC provides augmentation of transient stability. The $\theta - \omega$ curve of generator No.1 is shown in Fig.11.

Using of FC/TCR with aditional supplementary control signals provides significant improvement in damping of rotor oscillations as shown in Fig.12.

6. CONCLUSIONS

The paper presents a control strategy for transient stability augmentation and damping the power system oscillations due to large disturbances, using combined type of static VAR compensator.

The switching control of mechanically switched capacitor isbased on phase plane analysis. Two- insertions of the switched capacitor are required for rapid transient stability improvement.Optimal ellipse equation requries the equilibrium of the system with switched capacitor on (for the same mechanical power input), which can be calculated off-line by load flow calculations which will be stored in a look-up table.

The FC/TCR compensator with a speed or power deviation as a stabilizing signal is effective in damping the subsequent power system oscillations. Power supplementary signal is more effective than speed signal in damping rotor oscillations.

7. REFERENCES

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APPENDICES

1.The parameters of the single machine infinite bus system are

$M = 10$ s $X_d' = 0.29$ p.u $X_d = 0.8$ p.u

$X_{t1} = 0.12$ p.u $X_{t2} = 0.08$ p.u

The operating point considered is

$P_o = 1.0$ p.u $E\angle\delta_o = 1.115 \angle 48.2^0$ $V = 1.0$ P.U

The parameters of the FC/TCR compensator are

$T_r = 0.15$ s $K_t = 50$

2.The parameters of the 10-generator and 19-busbar system and load flow calculations are given in Reference [9].

The operating points of system generators are (base MVA = 1000)

No. of generator	P_o (p.u)	V_t (p.u)	E (p.u)	δ_o (deg.)
1	1.457	1.00	1.544	10.2
2	0.240	1.033	1.581	3.28
3	0.350	1.005	1.542	4.99
4	0.900	1.009	1.475	2.90
5	0.120	0.939	1.125	-2.50
6	0.550	1.067	1.328	-16.70
7	0.229	0.932	1.178	6.78
8	0.260	1.003	1.578	0.20
9	0.330	1.104	1.660	5.28
10	0.960	1.091	1.222	-20.50

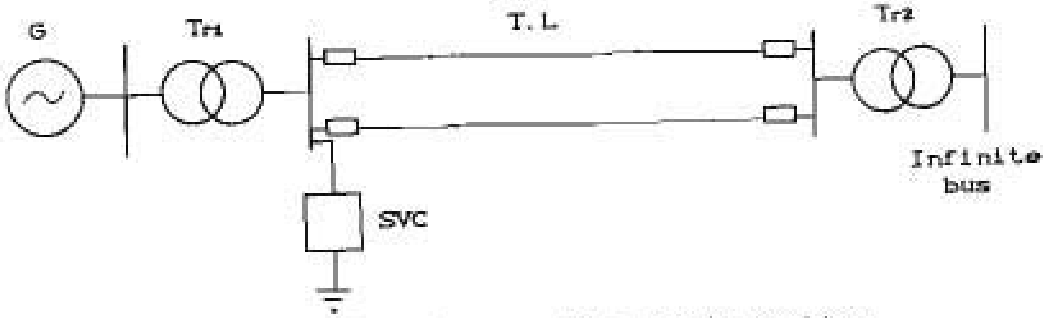

Fig.1 One-line diagram of a single machine connected to a large power system.

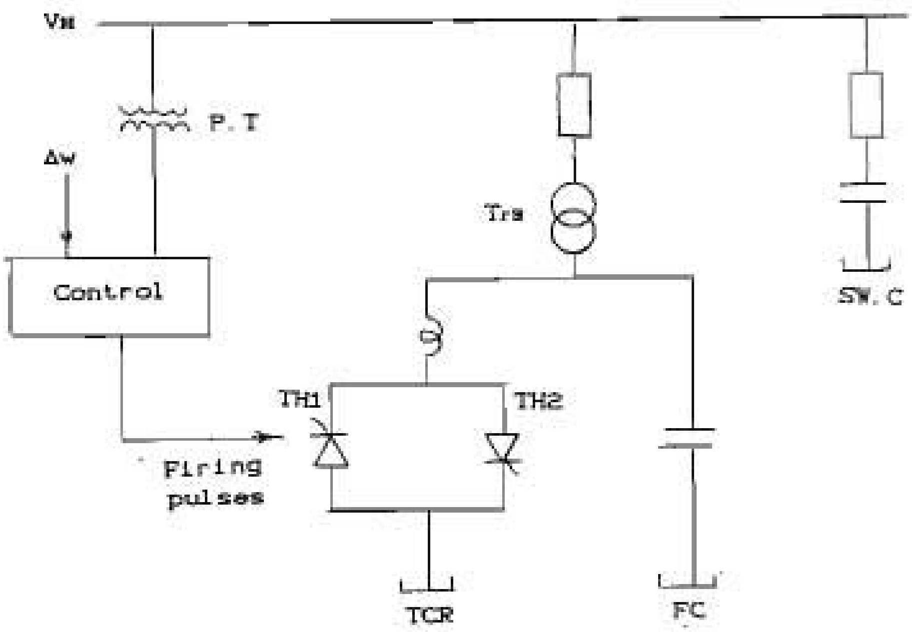

Fig.2(a) Combination type SVC

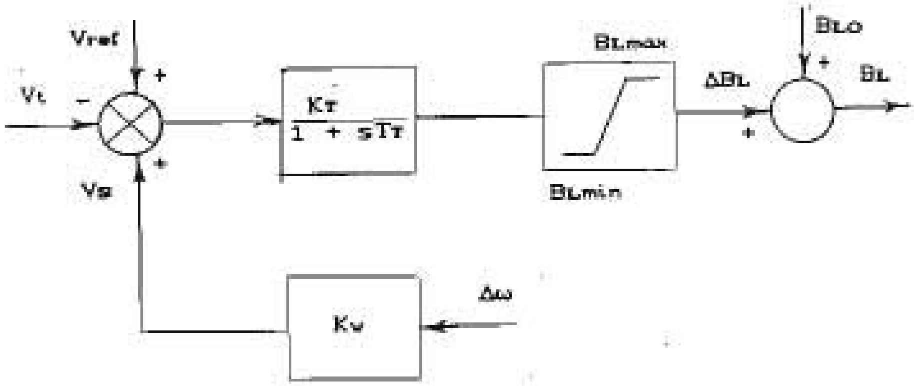

Fig.2(b) Control block diagram of SVC

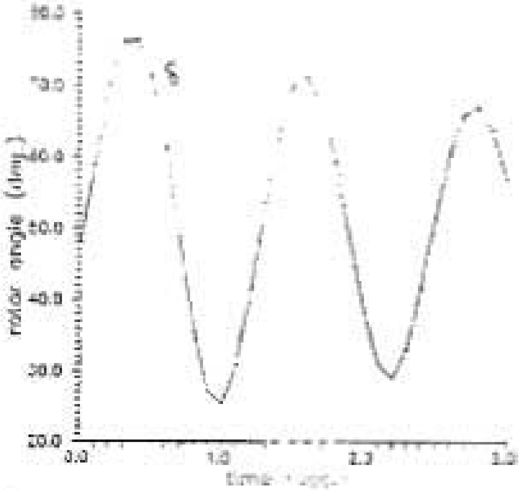

Fig.3(a) Response of rotor angle

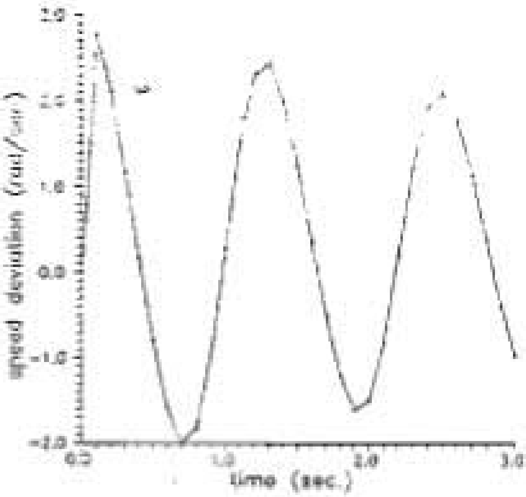

Fig.3(b) Speed response

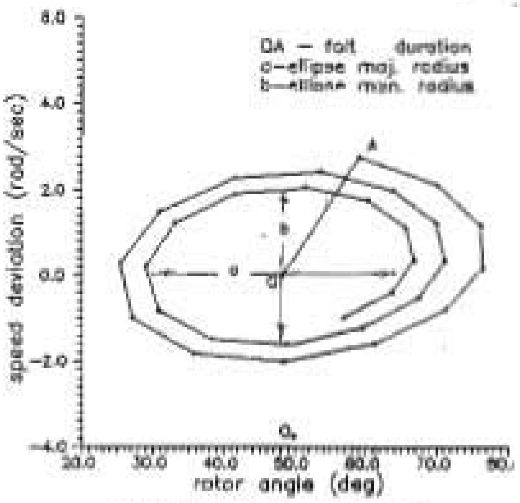

Fig.3(c) δ-ω response

Fig.3 Typical swing curves of remote generator.

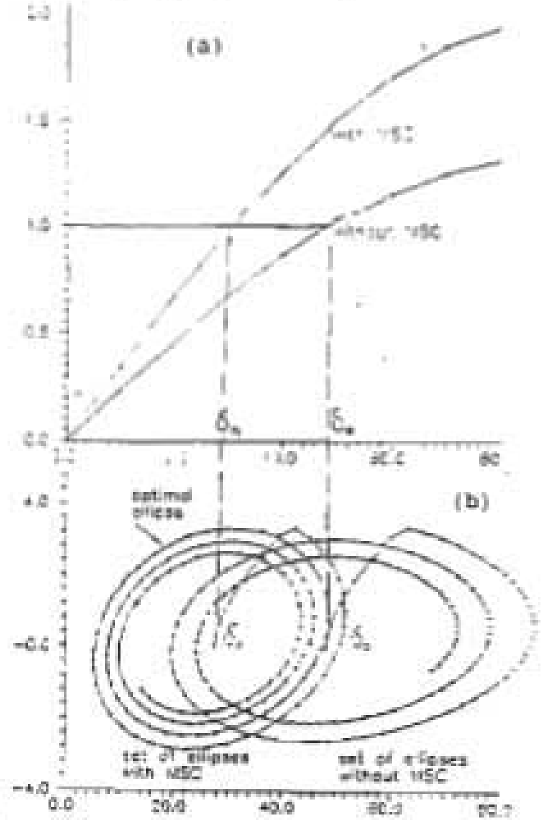

Fig.4 P-δ characteristics (a), δ-ω swing curves (b) with and without SW.C

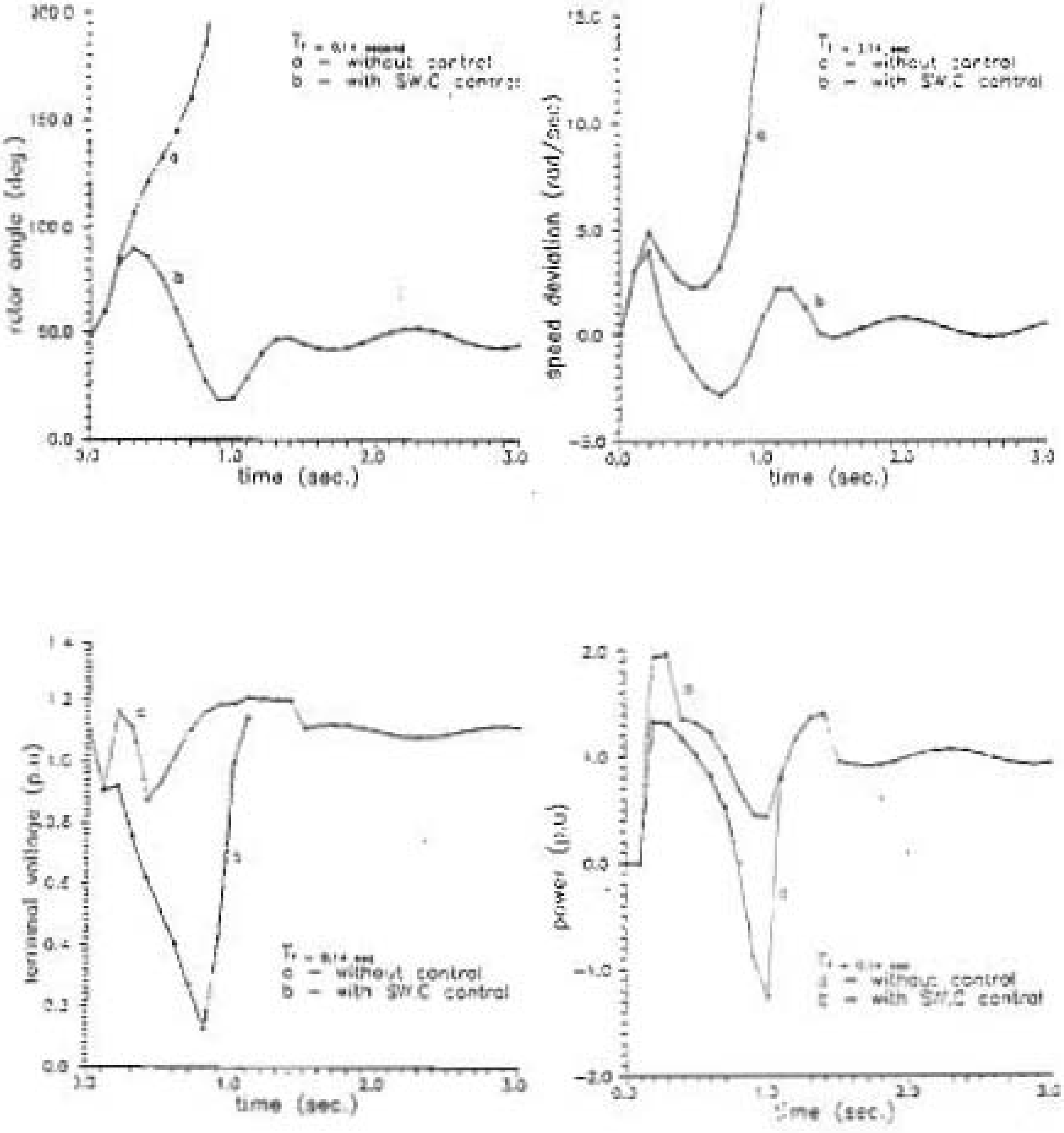

Fig. 5   Response of δ, ω, Vt
and P of system #1

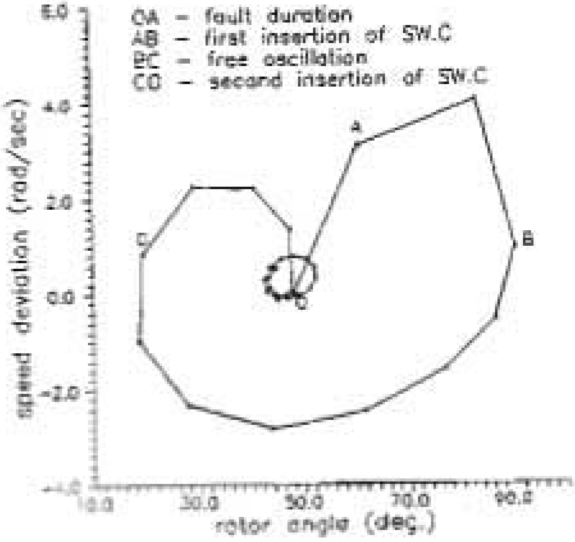

Fig. 6 Trajectory of δ-ω, using SW. capacitor

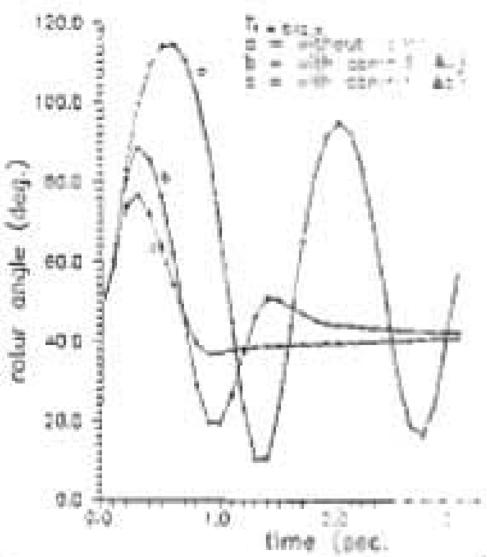

Fig.7

Rotor angle oscillation with and without FC/TCR control (Tr = 140 ms)

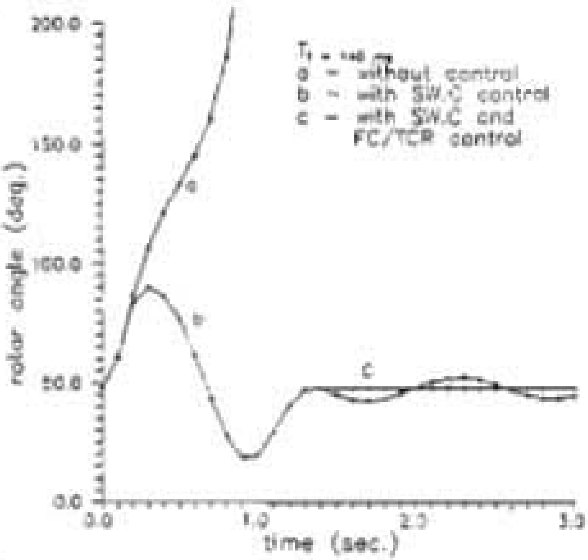

Fig.8 Rotor angle oscillation with SW.C and FC/TCR control (Tr = 140 ms)

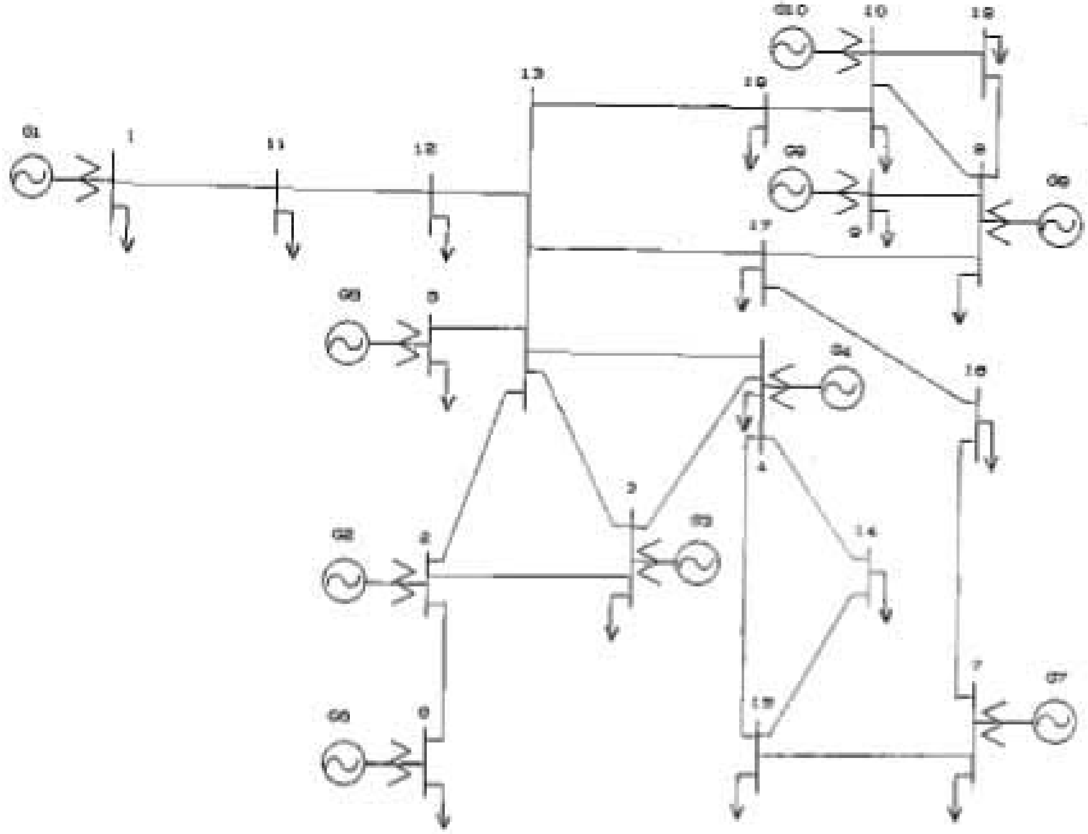

Fig.9 Single line diagram of the 10-generator & 19-bus system.

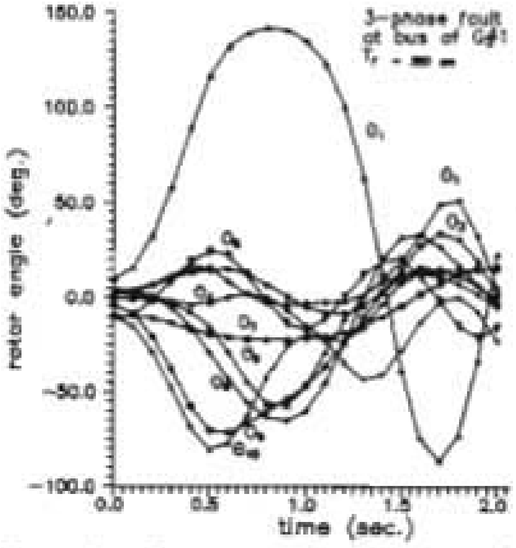

Fig.10 Response of rotor angle at Tr = 380 ms

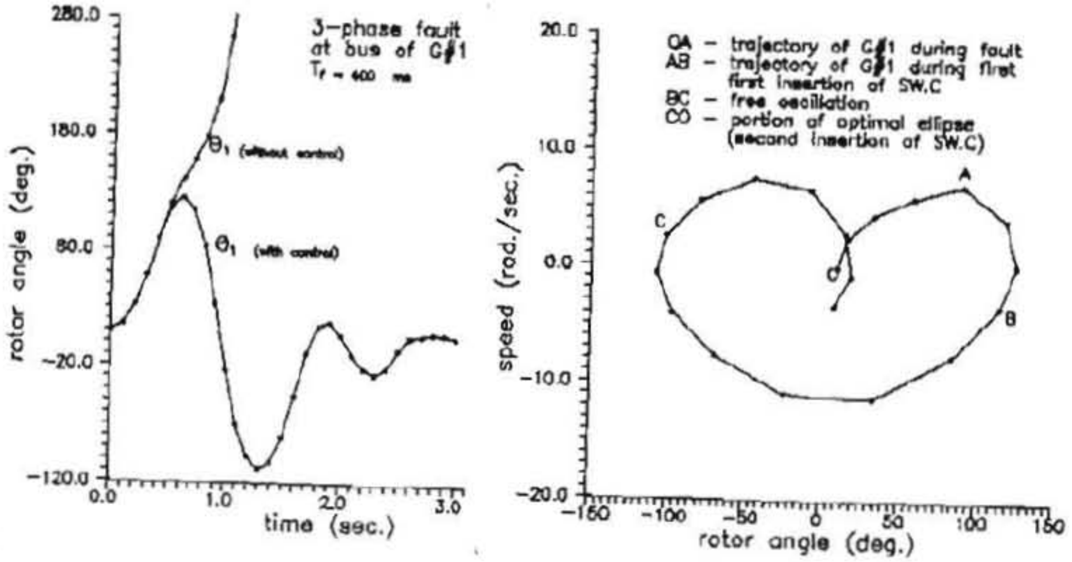

Fig.11 θ1 response with and without SW.capacitor

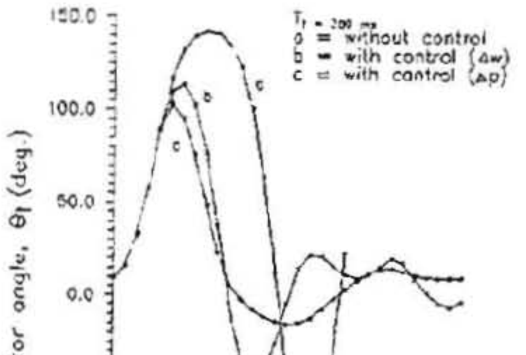

Fig.12 Damping of rotor angle of G1, using of FC-TCR