SSR을 제어하기 위한 새로운 캐패시터 스위칭방법에 관한 연구

論 文
45~1~10

New Capacitor Switching Schemes to Control Subsynchronous Resonance

李 勳 九* · 李 丞 桓** · 姜 承 旭*** · 韓 慶 熙§ · 鄭 然 澤§
(Hoon-Goo Lee · Seong-Hwan Lee · Seung-Wook Kang · Kyung-Hee Han · Yon-Tack Chung)

Abstract - Subsynchronous resonance(SSR) causes a torsional shaft torque on the generator. Damages resulting from the uncontrolled SSR have resulted in the breakdown in the shaft and costs for replacement power. This paper is to determine the feasibility of controlling SSR by the fast modulation of series compensation capacitors. The presence of subsynchronous currents in the system was detected by a subsynchronous relay which was modeled by the transient analysis of control systems(TACS) in electromagnetic transients pogram (EMTP). The capacitor segments were switched by bi-directional thyristor switches. These were modeled into EMTP. The strategy to switch the capacitors were modeled as a closed loop system. The paper proves that effective control of SSR can be obtained only by the detuning of the system and the removal or blocking of subsynchronous energy from the system.

Key Words : Series capacitor, Subsynchronous resonance(SSR), transient analysis of control systems(TACS), electromagnetic transients pogram (EMTP)

1. Introduction

The operation of a transmission line at a high level series compensation reduces the VAR losses on the power system which improves the power transfer and the control.

However, high level series compensation may produce SSR that may damage the generator shafts. Damages resulting from the uncontrolled SSR have resulted in many of loss due to the breakdown in the shaft and costs for replacement power [1]. So, many contributions have made in the field of damping of torsional oscillations which occur in a power system with series-capacitor compensated lines. For comparing the different techniques and investigating various SSR countermeasures, the IEEE SSR Working Group proposed a standard model known as the IEEE first benchmark model for computer simulations in 1977 [2]. The IEEE first benchmark model has been extensively employed for many years, although the model is a simple radial form of power system rarely encountered in practical power systems. In 1984, another more common type of power system model, the IEEE second benchmark model, was recommended by the same group [3]. Many strategies for the control of SSR have been proposed. Of interest to the current task is the work related to the control of SSR using switched capacitors. One of the schemes for the control of subsynchronous energy is the NGH Scheme, named after its invertor, N G Hingorani [4,5]. But, the disadvantage of this system is that it has to be installed on every line that participates in SSR and may be very costly.

The aim of this paper was the development of strategies to control SSR and simultaneously maintain a high level series compensation. The transmission line was selected as test system. This system has been tested in computer simulations on the second benchmark model, system-1. The switching operation was modeled using the TACS in EMTP. The transmission line system was modeled into the EMTP. The simulation calculated shaft torque, transmission line current, and capacitor bank segment voltages. Shaft torque oscillations were plotted. The growth rate of the oscillations was determined from these plots. The paper proved that effective control of SSR can be obtained only by the detuning of the system and the removal or blocking of subsynchronous energy from the system.

*正 會 員 : 忠南專門大 電子科 副教授 · 工博
**正 會 員 : 忠南專門大 電氣科 助教授
***正 會 員 : 上智專門大 電氣科 專任講師
§正 會 員 : 明知大 工大 電氣工學科 教授 · 工博
接受日字 : 1994年 9月 3日
1次 修正 : 1994年 11月 1日
2次 修正 : 1995年 4月 25日
3次 修正 : 1995年 10月 23日
4次 修正 : 1995年 12月 14日

2. System description and modelling

2.1 Model description

The EMTP representation of the second benchmark model is more complex than the first benchmark model. This test

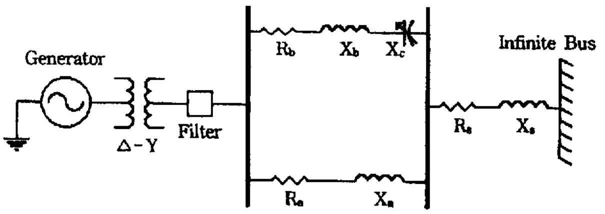


Fig. 1 Electrical Network Representation for the Second Benchmark Model System-1

network was developed by the IEEE working group on subsynchronous resonance. This benchmark model which deals with the so-called "parallel resonance" was divided into system-1 and system-2.

The system-2 model constitute two different generators and a single series compensated transmission line(For example, Y type).

The system-1 model constitute a synchronous generator feed to an infinite bus via two parallel lines; one of the lines is with series capacitor compensation. The electrical representation of the second benchmark model, system-1 is shown in Figure 1. The delta-star transformer is represented by a saturable model. The leakage resistance of the primary side is 0.00096[Ω] and the leakage reactance on the secondary side is 132.6[mH]. Capacitances of 0.1[㎌] are connected on the star side of the delta-star transformer, between the phases and ground. Oscillations are initiated by fault the line 'b' with a three phase to ground fault. The fault current is limited by a reactor of 2[H]. The fault is cleared after three cycles. The bus is modeled with three sinusoidal sources. The source impedance is a resistance of 3.5[Ω] and an inductance of 198.9[mH].

The circuit parameters are as follows. These are in per unit on a 100[MVA]/500[kV] base.

The transmission lines are modeled using both the positive and the zero sequence impedance. Line 'b' is compensated by a capacitor of 24.11[㎌]. This capacitance was divided into ten equal segments connected in series. Each segment is 241.1[㎌]. The capacitor segments were switched using EMTP's thyristor models. Back to back connected thyristors were used.

The mechanical part of the studied system is depicted in Figure 2 which is a mass-spring system containing four masses.

The high-pressure turbine (HP), the low-pressure turbine (LP), the generator (GEN), and the exciter(EX) are coupled on the same shaft. If the rotating machine is not a conventional, balanced, three phase synchronous generator, the user must use the universal machine. Otherwise, the user must use the EMTP's type 59 dynamic synchronous machine source component(an EMTP source by general classification). So, the EMTP's type 59 source is used [6]. The generator

Table 1 Circuit Parameters-Second Benchmark model output voltage is 17963.0[V] at 60[Hz]. The 3 phase MVA

Element	Positive Sequence[Ω]	Zero Sequence[Ω]
Line 'a' resistance - R_a	0.0067	0.0186
Line 'a' reactance - X_a	0.0739	0.210
Line 'b' resistance - R_b	0.0074	0.022
Line 'b' reactance - X_b	0.0800	0.240
Source resistance - R_s	0.0014	0.0014
Source reactance - X_s	0.030	0.030

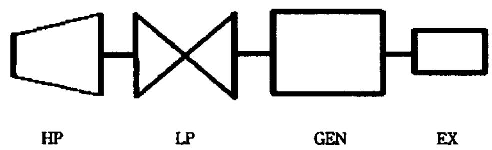


Fig. 2 The mass-spring system for system modeling

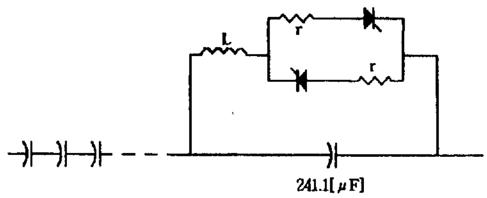


Fig. 3 Series capacitor and the switches

rating of the two pole machine is 600[MVA].

In figure 3, thyristor switches were connected in shunt with a few of the capacitor segments. These switches were protected with resistances or inductances connected in series with the antiparallel connection of the thyristor strings. The turn-on of the thyristor switches discharged the capacitors. Resistances(r) of 0.005[Ω] were added in series with the thyristor to represent their on-state resistance.

The machine electrical and mechanical data are tabulated in the following table.

Table 2 Machine Electrical Data

Elements	Data	Elements	Data
R_a	0.0045 [pu]	X_l	0.140 [pu]
X_d	1.650 [pu]	X_q	1.590 [pu]
X'_d	0.250 [pu]	X'_q	0.460 [pu]
X''_d	0.200[pu]	X''_q	0.200 [pu]
T'_{do}	4.50 [sec.]	T'_{qo}	0.55 [sec.]
T''_{do}	0.040 [sec.]	T''_{qo}	0.090 [sec.]
R_n	100.0 [pu]	X_n	100.0 [pu]
X_o	0.147 [pu]		

Table 3 Machine Mechanical Data

Mass	Inertia [Lbm ft^2]	Damping [Lb-ft/rad/sec]	Spring constant [Lb-ft/rad/sec]
EX	1383	4.3	4.39×10^6 97.97×10^6 50.12×10^6
GEN	176204	547.9	
LP	310729	966.2	
HP	49912	155.2	

Table 4 Mode Shapes

Rotor frequencies	Mode1 (24.65Hz)	Mode2 (32.39Hz)	Mode3 (51.1Hz)
Exciter	1.307	1.683	-102.6
Generator	1.00	1.00	1.00
LP-Turbine	-0.354	-1.345	-0.118
HP-Turbine	-1.365	4.813	0.0544

Table 5 Angular velocity of mass at rotor frequency

Mode	f_n[Hz]	σ_n[rad/sec]	H_n[pu]
1	24.65	.05	1.55
2	32.39	.05	9.39
3	51.10	.05	74.80

The inertia, damping and spring constants are given in the indicated physical units. The damping have been chosen proportional to inertia so that each mode has the same torsional damping in rad/sec. Therefore, the modal damping directly related to the viscous damping of the elements [3]. Where, f_n = rotor frequency, σ_n = torsional damping, H_n = $2.31 \times 10^{-10} \{\Sigma\ J_k\ (V_k/V_g)\}rpm^2$ / MVA (angular velocity of mass) and J_k = Inertia in lbm-ft^2.

2.2 Base case analysis

It was necessary that the behavior of the system, with respect to the occurrence of SSR, under different levels of line compensations should be known. Eigenvalue analysis was used to determine this. The analysis provided plots of the undamping in the system as a function of the percentage series compensation. The more the level of undamping, the less stable is the system.

Figure 4 shows the results of the eigenvalue analysis on the second benchmark model [3].

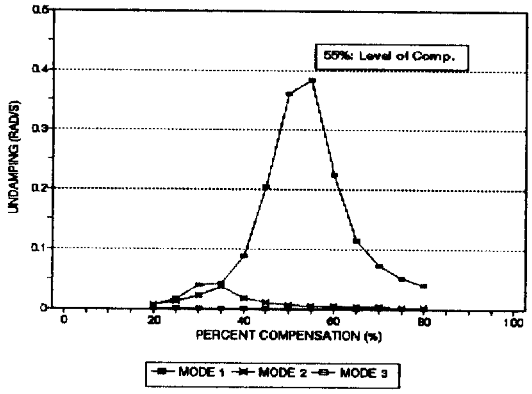
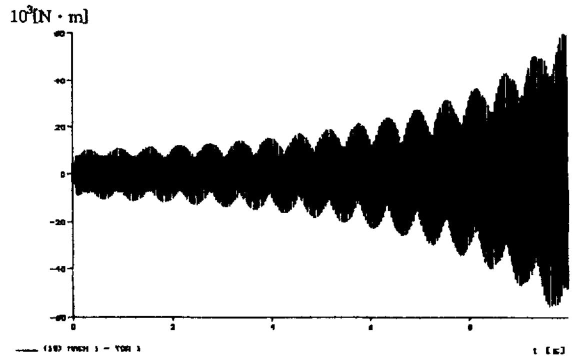


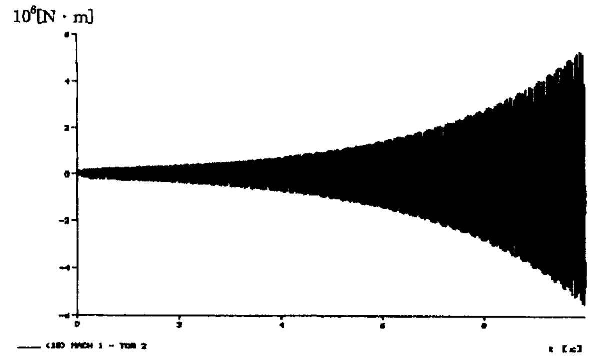
Fig. 4 Eigenvalue study result plotted- Percentage Compensation vs Undamping (Real part of Eigenvalue)

Table 6 System eigenvalues (rad/sec) at: pf =0.9 lagging and X_C/X_L = 55%

Modes	Real	Imaginary
3	.00061293	±j 322.31092907
2	.00508760	±j 203.54024729
1	.38302593	±j 155.23361253



(a) HP-LP



(b) LP-GEN

Fig. 5 Shaft torque variations of the Second Benchmark Model without control

Table 6 and figure 4 gives the system eigenvalues at the operating condition of X_c/X_l = 55%, and lists the eigenvalues of the system without control. It is obviously found that the eigenvalues of the mode 1 will be unstable for some X_c/X_l compensation degrees. The eigenvalues are based upon the following approximate relationship from reference [3,7]. Imaginary number = $f_n \times$ rad/sec.

Figure 4 indicates that the generator has the dominant mode of oscillation which correspond to the critical values of compensation. So, for the testing of the control strategies, the critical level of compensation was chosen.

The second benchmark model, without the thyristor control, was analyzed using the EMTP simulations. That is, the second benchmark model was simulated without the capacitive switching. The shaft torque was recorded and its growth rate was calculated. The SSR was initiated in the system by a short duration ground fault.

Figure 5 shows uncontrolled shaft torque growth. If these oscillations are not controlled, Such a growth can results in permanent damage to the shaft.

3. Control strategy

3.1 General method of investigation

The aim of this paper was to develop strategies for the control of SSR by the fast regulations of series compensation capacitors. Eigenvalue analysis was used to identify the most critical conditions for occurrence of subsynchronous oscillations. The approach to control the subsynchronous energy in electrical systems was the reduction of coupling between the electrical and mechanical systems by detuning the system and the removal of subsynchronous energy from the system.

(1) Detuning techniques: The series compensation is controlled to detune the system. The detuning decreases the amount of undamping in the system. As an example, the strong SSR are generated in the second benchmark model when the system is operated at 55[%] compensation. This can be seen in the eigenvalue analysis plots, Figure 4.

(2) Removal of subsynchronous energy: The firing of the thyristors discharges the capacitor and removes energy from the system. It is expected that removal of energy will damp out the oscillations in the system.

It is also possible that the combination of the two strategies may be used to yield better and faster control. Control strategies were developed using the above concepts and by the analysis of the thyristor controlled circuit capability.

3.2 Modulated Control method

3.2.1 Sequential switching of capacitors

The compensating capacitor was divided into a ten segment bank. Two of the segments were controlled by bi-directional thyristor switches. This permitted the fine tuning of the compensation. The efficient operation of the system transmission line requires a fixed level of compensation. For example, in the second benchmark model the desired level of compensation is 55[%]. When a SSR condition is present in the system, the system is detuned by changing the compensation of the system. This detuning reduces the level of undamping in the system and will damp out the oscillations. The system was disturbed by a short duration ground fault. The presence of SSR in the system was detected by monitoring the transmission line current. The transmission line current was fed into a subsynchronous relay.

Figure 6 shows the filter and the detector of SSR. The relay consists of a set of filters. The filters are notch type and are tuned to the nodal frequencies of the system. These filters are used to eliminates the 60[Hz] component and calculates the RMS value of the subsynchronous currents. Arizona public service company provided the function parameters of relay and this relay was modeled in the EMTP program [8]. The MSW3A is the node between transformer and filter of figure 1. The ONE, TWO, THREE and FOUR are the transfer functions or S-blocks of TACS.

The output of the relay is used to control the switching of the bi-directional switches. When the subsynchronous current has a magnitude greater than a preselected threshold value, the thyristor switches are activated to short the capacitor segments. The elimination of a capacitor segment detune the system. The line current was monitored to trace RMS magnitude of the subsynchronous currents. If this magnitude increased, one more of the capacitor segments was shorted. The logic was devised such that if the amplitude of the subsynchronous current decreased, the capacitors would be reintroduced into the circuit and the original level of compensation restored.

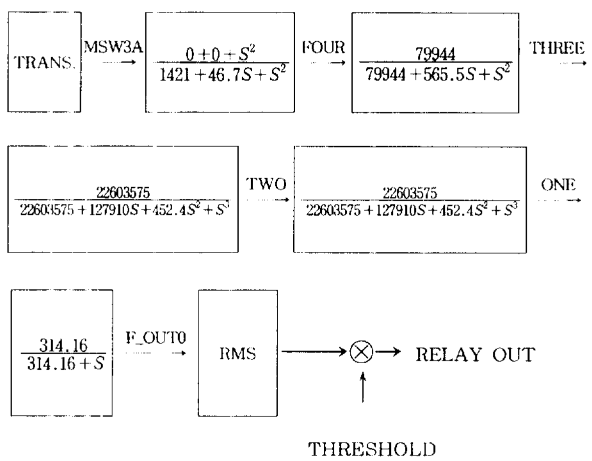


Fig. 6 Filter and the detector of SSR

3.2.2 Improved NGH scheme

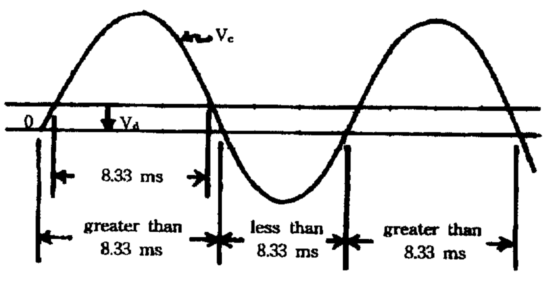
The basis of the NGH-SSR damping scheme will be explained with reference to Figure 7a. First consider the 60[Hz] voltage V_c, combined with a DC voltage. For the combined voltage, it is seen that some half cycles are longer than the nominal 60[Hz] half cycle period of 1000/120 = 8.33[ms]. Also consider the 60[Hz] voltage V_c (Figure 7b) combined with a subsynchronous frequency voltage V_{ss}. Again, it is seen that the resulting voltage V_{ct} has some half cycles which are longer than 8.33[ms]. Similarly, any combination of a base signal (60[Hz]) with DC and subsynchronous frequencies would result in some half cycles longer than the nominal half cycle period(8.33[ms]). Conversely, if there was no DC or any subsynchronous components with 60[Hz], then each half cycle would be 8.33[ms]. For the present discussion, these waveforms represent voltage across the series capacitor. The hypothesis of the NGH scheme is that the unbalanced charge (energy) in the series compensation capacitor is caused to produce oscillations. So, if there has been cancellation of reactances in the capacitors and inductors in the system, the oscillation growth will stop. If this unbalance is reduced, then the system would be effectively detuned to any frequency other than 60[Hz].

The idea is simply a method of dissipating capacitor charges, if and when its half cycle voltage period exceeds the desired half cycle period of 8.33[ms] [4]. However, unlike the NGH scheme, this scheme uses continuous changes in the firing angle of the capacitor shorting switches. The fraction of the AC time period for which the capacitor segments are shorted is made to be a function of the magnitude of the subsynchronous current in the system. The subsynchronous relay discussed earlier is used to give a measure of the magnitude of the subsynchronous currents present in the system. The output of the filter is converted into a proportional firing angle for the switches. The amount of subsynchronous energy taken out of the system is varied. More energy is removed when the magnitude of the subsynchronous current is high. This is done by decreasing the firing angle of the thyristor switches. Figure 8 shows the voltage across the switched capacitor segment. Here the changes in the time for which the capacitor is shorted can beobserved.

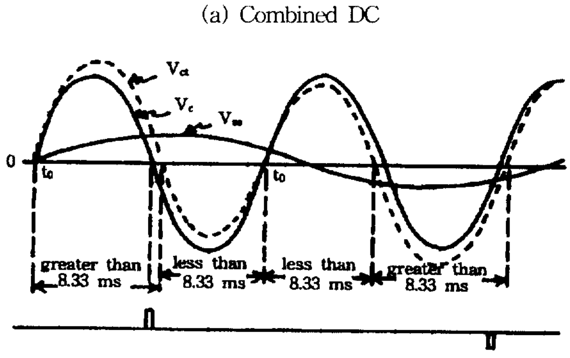
When the system without control, the SSR relay measures the RMS value (Maximum value÷40[A]) of the subsysnchronous line current. And then, the measured current value is converted to a firing angle between 180-170 degrees. The conversion algorithm uses the following linear relationship:

$$\alpha(I_{ss}) = 180 - [k \times I_{ss}] \quad (1)$$

Here 'k' is a constant of proportionality and is typically equal to 0.25 and Iss is the subsynchronous current(RMS value) in the system. The capacitor is shorted after α degrees. This removes subsynchron- ous energy from the circuit.



(a) Combined DC



(b) Combined subsynchronous voltage

Fig. 7 60[Hz] voltage combined with DC and subsynchronous voltage

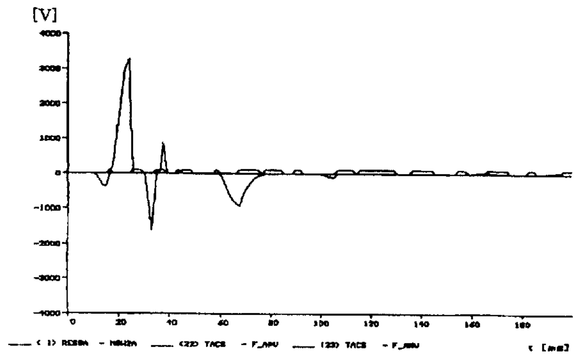


Fig. 8 Capacitor voltage and thyristor firing pulses

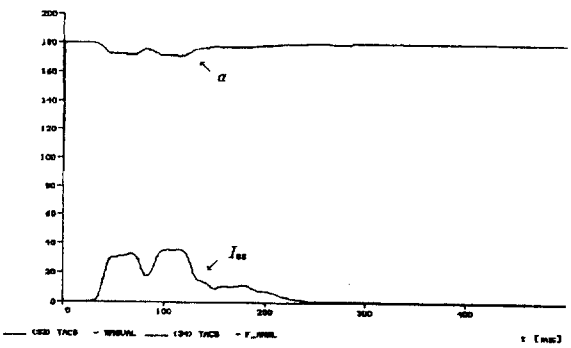


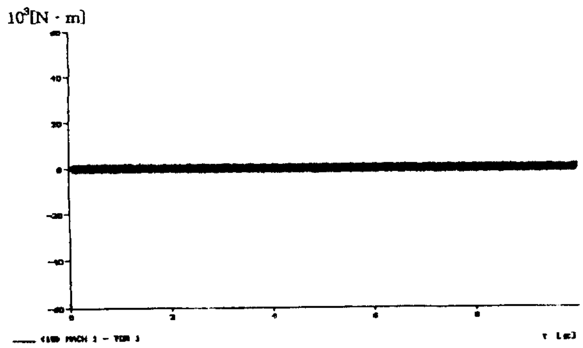
Fig. 9 Firing angle variations and the subsynchronous current

That is, when the presence of SSR is detected, the thyristor switches are activated. As long as the presence of SSR is detected by the filter, the thyristor switches are fired. The firing angle of the thyristor switches is made dependent on the magnitude of the subsynchronous current in the system. A measure of the subsynchronous current was obtained by using the subsynchronous filter and calculating the rms value of the subsynchronous frequency components. Eq. 1 is used as the control function.

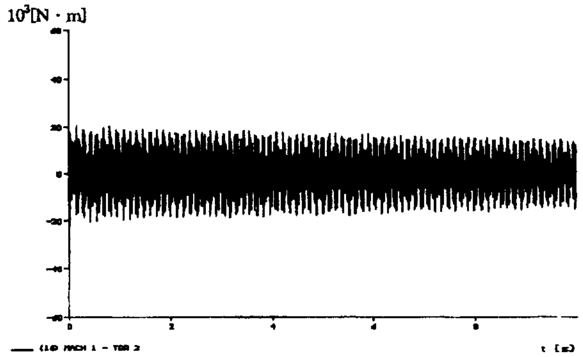
The firing angle of the thyristor switches was decreased as the magnitude of the subsynchronous current increased. Figure 9 shows a typical plot of the variation in the firing angle and the related subsynchronous current in the system. The variations of the firing angle with the changes in the current magnitude can be observed.

When there is no subsynchronous current in the system, or its magnitude is small, the inductor is not inserted in parallel with the capacitor. The transmission line now operates at its desired level of compensation. The thyristor switches are not fired. Or according to Eq. 1 the firing angle is 180 degrees.

When the presence of subsynchronous currents is detected in the transmission line, initiated by a line to ground fault, the switches are slowly introduced into the circuit. This blocks the subsynchronous energy from flowing through and causing shaft torque oscillations.



(a) HP-LP



(b) LP-GEN

Fig. 10 Shaft torque variations of the Second Benchmark Model with control

The figure 10 shows the results on the Second Benchmark. It can be seen that the growth of shaft torque oscillations has been decreased.

4. Conclusion

The purpose of this paper was to determine the feasibility of controlling SSR by the control of series compensation. Different series compensation control strategies were developed and tested using EMTP simulation. The results of the study are summarized as follows:

(1) An EMTP model was developed for a back-to- back thyristor controlled series capacitor. This model utilized practical values obtained from industry.

(2) For the detection of SSR the concept of a SSR relay was adapted and incorporated in the EMTP model.

(3) The developed EMTP model was controlled by a closed loop system. This model incorporated the subsynchronous relay, transfer function block, logic for the firing of the thyristors. This control system was realized using the TACS in EMTP.

(4) This strategy removed variable amount of energy from the system by firing the thyristors before zero crossing. The firing time depend on the magnitude of subsynchronous current. The strategy was tested on the second benchmark model. The growth of subsynchronous oscillation in both the test system was controlled by switching of 10[%] of the compensation capacitance.

In the future, it is expected that the task force plans to remove the SSR on the generator and we hope this kind of study will continue.

Reference

[1] 한국전력공사 기술연구원 "전력계통 과도해석 프로그램의 이론 및 활용에 관한 연구" KRC-89S-J07, Vol. III, pp. 268 -274, Jan, 1991.

[2] IEEE Subsynchronous Resonance Task Force of the Dynamic System Performance Working Group "First Benchmark Model for computer simulation of Subsynch-ronous resonance" IEEE Transaction on Power Apparatus and Systems, Vol. PAS-96, No.5, pp. 1565-1572, Sep/Oct, 1977.

[3] IEEE Subsynchronous Resonance Working Group "Second Benchmark Model for computer simulation of Subsynch-ronous resonance" IEEE/ PES 1984 Summer Meeting, Seattle, Washing- ton, pp.1-8, July 15-20, 1984.

[4] N. G.Hingorani "A new Scheme for Subsynchron- ous Resonance Damping of Torsional Oscillations and Trans-ient Torque-part I" IEEE Transaction on Power Apparatus and Systems, Vol. PAS- 100, No.4, pp.1852-1855, April, 1981.

[5] N. G. Hingorani "Prototype NGH Subsynchronous resonance d amping scheme,Part I-Field installa- tion and ope rating experience" IEEE Trans- actions on Power Systems, Vol. PWRS-2, No. 4, pp. 1034-1039, Nov. 1987.

[6] The EMTP Development Coordination Group and Electric Power Research Institute "The Electro- magnetic Transients Program(EMTP) Version 1.0, Revised Rule Book" EL-4541-CCMP, Vol. 1 Research Project 2149-4, pp. 10-48~ 10-43, Apr. 1986.

[7] Li Wang "Damping of Torsional Oscillations using Excitation Control of Synchronous Generator: The IEEE Second Benchmark Model Investigation" IEEE Transactions on Energy Conversion, Vol 6, No. 1, pp. 47-54, Mar. 1991.

[8] G. G. Karady, Hoon-Goo Lee, Scott Helbing and Pramod parihar "Advanced Concept Studies Related Flexible AC Transmission System" EPRI Project, RFP4000-6, 1992.

저 자 소 개

이 훈 구 (李 勳 九)

1948년 4월 27일생. 1971년 명지대 공대 전기공학과 졸업. 1989년 동 대학원 전기공학과 졸업(공박). 1991~1992년 미국 아리조나주립대학교 객원교수, 현재 충남전문대학 전자과 부교수

한 경 희 (韓 慶 熙)

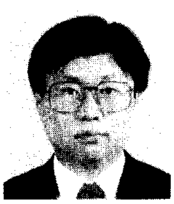
1943년 4월 9일생. 1967년 명지대 공대 전기공학과 졸업. 1983년 일본 나고야대 대학원 전기공학과 졸업(공박). 현재 명지대 공대 전기공학과 교수

이 승 환 (李 丞 桓)

1962년 2월 18일생. 1984년 명지대 공대 전기공학과 졸업. 1986년 동 대학원 전기공학과 졸업(석사). 현재 동 대학원 전기공학과 박사과정 수료. 충남전문대학 전기과 조교수

정 연 택 (鄭 然 澤)

1931년 4월 29일생. 1955년 서울대 공대 전기공학과 졸업(공박). 1978년 일본 동경공업대학 객원연구원. 명지대 부총장 및 당학회 부회장 역임. 현재 명지대 공대 전기공학과 교수



강 승 욱 (姜 承 旭)

1958년 4월 13일생. 1982년 명지대 공대 전기공학과 졸업. 1984년 동 대학원 전기공학과 졸업(석사). 1985년~1992년 현대중전기(주) 기술연구소 연구원. 현재 동 대학원 전기공학과 박사과정 수료, 안동 상지전문대학 전기과 전임강사