論文 5-4-2

# 약한 계통에서 동기조상기의 여자 시스템에 따른 HVDC 시스템의 과도 성능 분석

金 燦 起

# Dynamic Performance of HVDC according to Excitation System Characteristics of Synchronous Compensator in a Weak AC System

Chan-Ki Kim

요 약

수전단의 관성이 0(수전단에 발전력이 전혀 없는 경우)인 약한 계통에서는 HVDC가 재기동과 무효전력 보상을 위해서 동기조상기의 존재는 필수적이다. 동기조상기의 주된 목적이 무효전력을 보상하는 것이지만 SVC나 STACON과 같은 무효전력 보상장치는 HVDC시스템을 재기동(HVDC에서는 Black-Start라 부른다)시킬 수 있는 능력을 가지고 있지 못하기 때문에 동기조상기가 발전력이 없는 약한 계통에서는 유일한 대안이다. 동기조상기는 발전기의 일종으로서 무효전력을 조정하는 여자 시스템의 종류에 따라 다른 특성을 가지고 있다. 정지형 여자 시스템은 속응성과 보수 유지의 간편성 때문에 많이 각광받고 있는 형태임에도 불구하고 시스템이 가지고 있는 본질적인 결함 때문에 약한 계통에 연결된 경우에는 많은 문제점을 노출시키고 있다. 반면에 AC 회전형 여자 시스템은 속응성이 낮음에도 불구하고 여자기의 공급전원이 안정하다는 장점을 가지고 있다.

본 논문에서는 이러한 여자 시스템의 장단점을 분석하고 정지형 여자 시스템의 장점과 AC 회전형 여자 시스템의 장점을 결합한 새로운 여자 시스템을 제안하였다. 제안된 시스템은 HVDC 시스템에 연결된 경우에 좋은 제어 특성을 보여 주었으며 결과는 PSCAD/EMTDC를 이용하여 확인하였다.

ABSTRACT

This paper analyses with the dynamic performance of HVDC System connected to a weak AC system for varying exciter characteristics of synchronous machines connected at the converter bus. Conventionally capacitors are used to supply reactive power requirement at a strong converter bus. However the installation of synchronous machine is essential in a isolated weak network to re-start after a shutdown of HVDC and to increase strength. The dynamic performance of a synchronous machine depends on the characteristics depends on its exciter characteristics. In this paper, several exciter types are used to investigate their effect on the dynamic performance of the HVDC system and modifications to standard exciter topologies are suggested to mitigate observed problems.

**Keywords** : HVDC, Synchronous compensator(S.C), Exciter

## 1. INTRODUCTION

Over long distances bulk power transfer can be carried out by HVDC connection cheaper than by a long distance AC transmission line. Also, bulk power of HVDC transmission scheme may be transmitted through very long cables or across borders where the two AC systems are not synchronized or operating at different frequencies.

HVDC converters(both rectifiers or inverters) draw lagging reactive power from the AC system in the amount of about 60% of the real power. Usually HVDC systems are fully compensated for reactive power at the converter bus to improve system regulation and reduce transmission losses. Variation in DC power changes the reactive power requirement of the converter and hence tends to cause change of AC voltage. For strong AC system, these fluctuations are tolerable and we can use fixed capacitors to provide reactive power. However, these changes are particularly significant if the AC system is weak as they can lead to system instability. Hence we must use dynamically adjustable compensator schemes. Static Var Compensator (SVC), Static Condensor (STATCON) or Synchronous Compensator are the commonly used dynamic compensator schemes.

Nyati et. al. have shown that static compensators provide much faster system response compared to the synchronous compensators[1]. Dr. Gole et .al have shown that with modern fast acting synchronous compensators, the use of proper mix SVCs and synchronous compensators is the best choice for HVDC systems connected to very weak AC system[2].

For the extreme case of a receiving system of zero inertia (no generation), a conventional inverter cannot start after even a momentary interruption of D.C power. A synchronous machine in the receiving system is generally the only practical solution in such situations.

The normal operation of synchronous machine with a static exciter does not usually pose any major problems. However, during AC line-faults or in the case of connection to a weak AC network, synchronous machine with a fast field forcing bus-fed static exciter has a drawback, which may cause system instability. This is because the output voltage of the static exciter is dependent on the generator terminal voltage that is controlled by the static exciter.

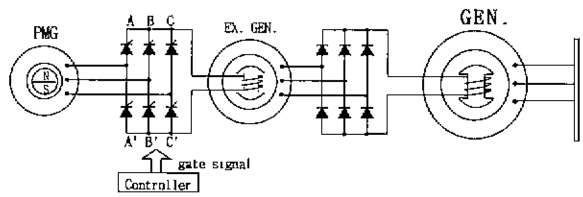
This paper investigates the problem represented above and proposes a solution. The investigation is performed by time domain digital simulation using EMTDC program.

## 2. A EXCITATION SYSTEM REVIEW[3]

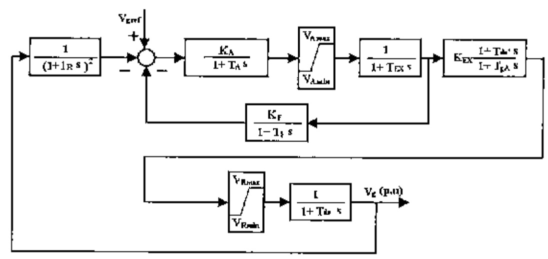
The IEEE has classified excitation systems currently in use into 12 models. From a system characteristics point of view, excitation system is classified 3 types- DC, AC and static type. Because the DC-type exciters are gradually being phased out, this paper discusses only AC and static type exciters.

### 2.1 AC Rotating Excitation System

Fig. 1 shows an AC rotating excitation system that consists of a Permanent Magnet Generator (PMG) with controlled rectifier and exciter generator with non-controlled rectifier.




(a) Schematic diagram of AC rotating excitation system



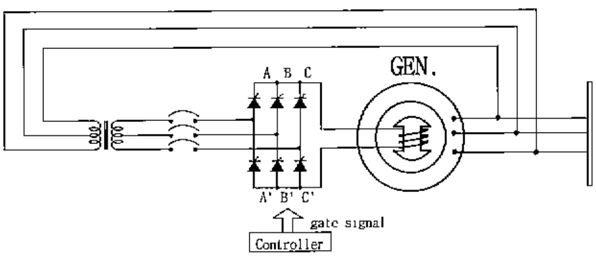
(b) AC rotating excitation system modeling

Fig. 1 Conventional AC excitation system

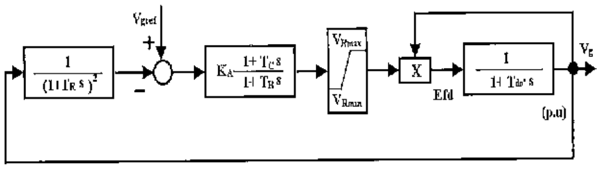
In this system, the exciter is on the same shaft as the turbine generator. The AC output of exciter is rectified by either a controlled or non-controlled rectifier to produce the direct current needed for the generator field. The rectifiers may be stationary or rotating. This system is more stable than a static excitation system because exciter power is not supplied by the generator terminals.

### 2.2 Static Excitation System

The excitation system shown in Fig. 2 consists of a synchronous generator and a controlled converter. The excitation power is supplied through a transformer from the generator terminals. Some of the advantages of this system include small inherent time constant, lower cost and easy maintenance. However, during system-fault conditions available excitation system ceiling voltage is diminished because the exciter output voltage is dependent on the AC system input voltage.




(a) Schematic diagram of static excitation system.




(b) Static excitation system modeling

Fig 2 Conventional static excitation system.

### 2.3 Controller Design of Static Exciter System

The controller design of static excitation shown in Fig. 2 (b) is follow as[4]:

The steady state gain ( $K_A$ ) of the exciter, is designed as per equation (1). The secondary voltage of excitation transformer( $V_2$ ) is designed as per equation (2).

$$K_A \geq \frac{V_{fN} - V_{f0}}{V_{f0}} \times \frac{100}{\varepsilon} \quad (1)$$

$$V_2 = \frac{\pi (V_P \times V_{f0} + V_{fD})}{3\sqrt{2} \times (\cos \alpha - 0.5 \times Z_T)} \quad (2)$$

where, $V_{fN}$ is full-load field voltage, $V_{f0}$ is no-load field voltage, $Z_T$ is transformer impedance, $V_{fD}$ is thyristor voltage drop, $\varepsilon$ is a voltage variation rate(%) and $V_P$ is a ceiling voltage coefficient of exciter.

The excitation system controller has a lead-lag compensator which has a steady state gain $K_A$ and the time constants $T_C$ and $T_B$. The transient gain $K_T$ of this controller expressed in terms of $K_A$, $T_C$ and $T_B$ is as given by equations (3 - 6) using gain margin and phase margin method of analysis. These equations are given below:

$$K_T = K_A T_C / T_B \quad (3)$$

$$K_T \geq V_R max / \triangle V_g \quad (4)$$

$$K_T / T_{do}' = \omega_c \quad (5)$$

$$1/T_C \leq \omega_c / n (\text{where, } n \geq 2) \quad (6)$$

where, $\triangle V_g$ is a sudden reduction rate of generator voltage.

As can be seen from these equations, the transient gain is also a function of the ceiling voltage $V_{Rmax}$. This ceiling voltage is a significant factor in determining the dynamic performance of the exciter.

## 3. HVDC WITH SYNCHRONOUS COMPENSATOR IN WEAK AC SYSTEM

### 3.1 System Study

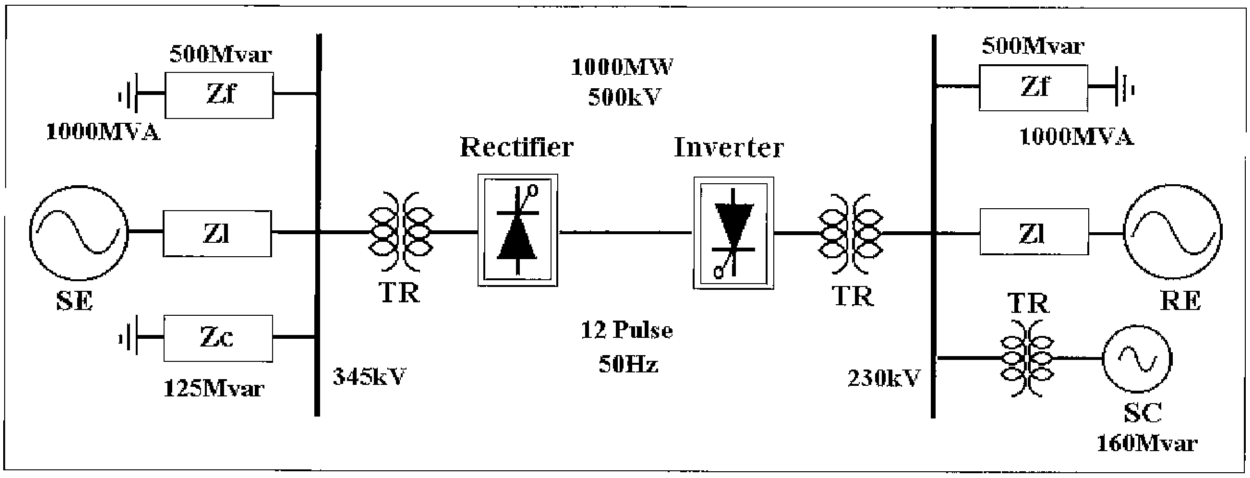



Fig. 3 HVDC model network at inverter side based on CIGRE model

Fig. 3 shows the inverter side of the study system. The DC controls of the study system are identical to the system in the CIGRE benchmark model[5]. The study system models a 1000MW, 500kV, 12 pulse, Monopolar HVDC system connected to a weak AC system. The inverter Short Circuit Ratio (SCR) is 2.5∠-80 and Effective SCR (ESCR) is 1.9 ∠-60. Fixed capacitors provide 500MVAr at rated voltage and the remaining reactive power requirement of the converter is supplied by the synchronous condenser of rating 165/+300 MVAr.

### 3.2 Characteristics Analysis of System Case

Fig. 4 shows DC voltage waveforms with static exciter and rotating exciter. The effective ceiling voltage for the exciter in both cases is 6 [p.u].

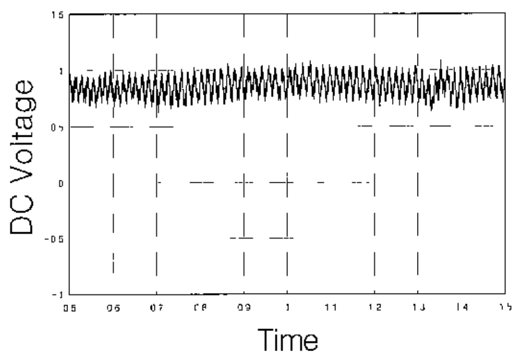
Table 1 Static exciter parameters

| | |
|---|---|
| $K_A$ | 150 |
| $T_B$ | 0.1[s] |
| $T_C$ | 0.375[s] |
| $T_{do}'$ | 2[s] |
| $\omega_c$ | 10[dB] |

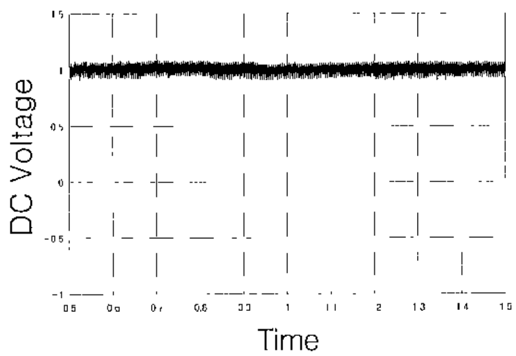
Table 2 Rotating exciter parameters

| | | | |
|---|---|---|---|
| $K_A$ | 37.5 | $K_{EX}$ | 4 |
| $T_A$ | 0.01[s] | $T_{gA}$ | 1[s] |
| $T_{EX}$ | 0.2[s] | $T_F$ | 0.1[s] |
| $T_{do}'$ | 2[s] | $K_F$ | 0.01[s] |
| $\omega_c$ | 10[dB) | $V_{Amax}$ | 1.0[p.u] |

Other control parameters are given in Table 1 for static exciters and in Table 2 for rotating exciter. In both cases the system in running in steady state. However, with static exciter the DC voltage shows oscillations (near fundamental frequency) of considerable magnitude as a result of fluctuations in the AC voltage caused by synchronous condenser exciter interactions with the AC system voltage. If the AC system is strong, the effect of interaction would have been negligible. In a weak system, these interactions could easily lead to system instability as shown in the next figure. Note that the high frequency oscillations in these waveforms are commutation notches characteristic of 12 pulse HVDC system and are present in both cases.

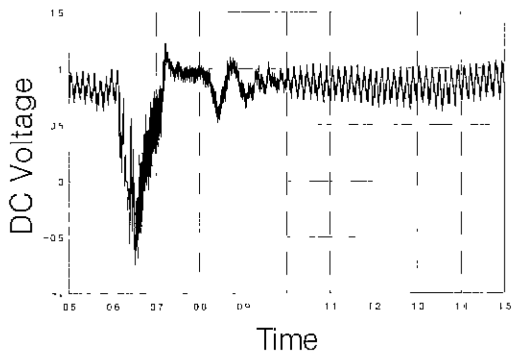



(a) Static exciter

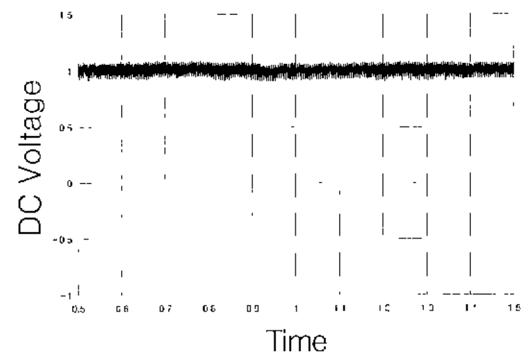



(b) AC rotating exciter

Fig. 4 DC voltage of HVDC according to exciter type with $V_R$max of 6 p.u.




(a) Static exciter




(b) AC rotating exciter

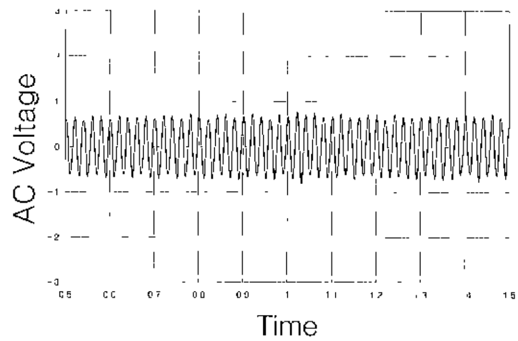
Fig. 5 DC voltage of HVDC according to exciter type with $V_R$max of 8 [p.u].

Fig. 5 shows the same system as in Fig. 4 except that the effective ceiling voltages of the exciters are changed to $V_R$max to 8 [p.u]. In this case, $T_B$ (0.194) and $T_C$(0.07) time constants of the static exciter are adjusted as per equations (10-13) so that $K_A$, $T_{do}'$ and $\omega_c$ are the same those for cases shown in Fig. 5. Note that the system with static exciter is unstable even during steady state operation where as the system with rotating exciter response is not affected.

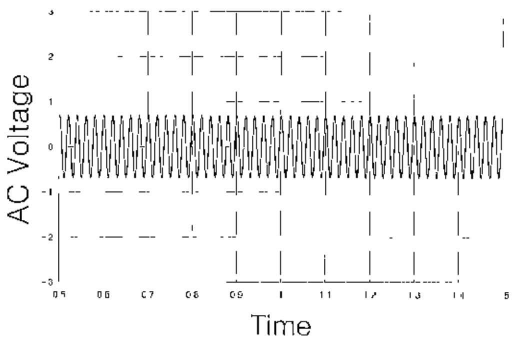
To understand this phenomena further, the AC system voltages waveforms for the case shown in Fig. 5 are shown in Fig. 6. Note that in Fig. 6(a) with static exciter, the AC system voltage has subharmonic frequency as a result of the interaction of the excitation system on the terminal voltage.

These oscillations are absent in the Fig. 6(b) with rotating exciter.

Now that we have seen that the conventional static exciter is unstable with HVDC systems connected to weak AC system, same tests were repeated with differently tuned gains for the HVDC controller (gamma controller) and the exciter itself. Fig. 7 (a) shows the DC voltage of HVDC w hen HVDC controller gain is tuned and Fig. 7 (b) when the exciter gain is tuned. From Fig. 7, the improvement, if any, was very insufficient to change the unstable behavior of the static exciter at higher field forcing limits.

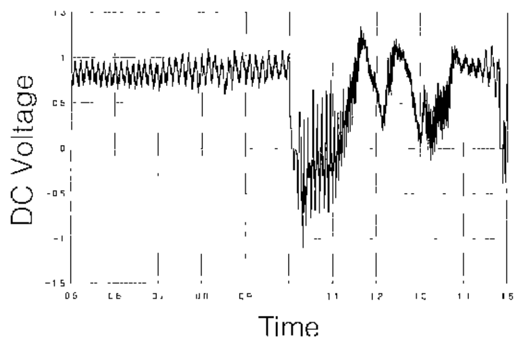


(a) Static exciter

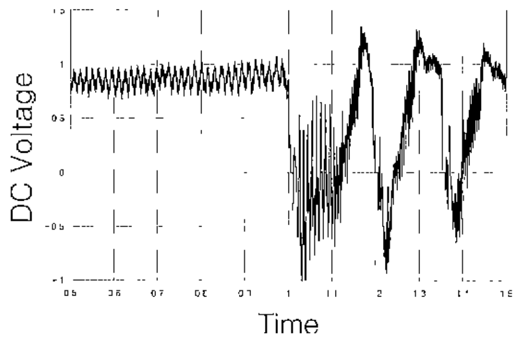


(b) AC rotating exciter

Fig 6 AC voltage of AC network according to exciter type



(a) With tuned HVDC gains



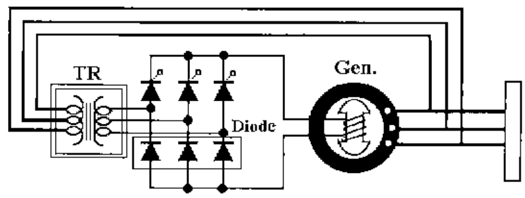
(b) With tuned exciter gains

Fig 7 DC voltage of HVDC with static exciter fed synchronous compensator

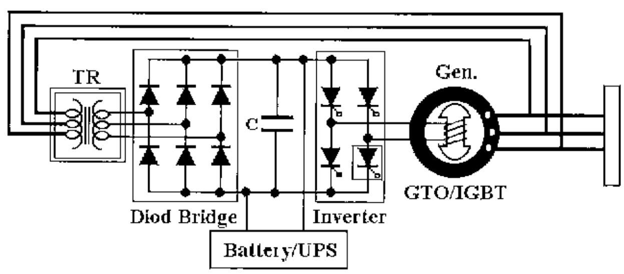
### 3.3 System Response with Modified Static Exciter Systems

The static exciter is modified as shown in Fig. 8(a) by replacing the thyristors in the lower arm of the rectifier with diodes.

The effect of this modification is that $V_R min$ is 0. To show how it affects the HVDC system behavior, an AC single phase fault was shown. Fig. 9 (a) shows the DC voltage response with modified exciter shown in Fig 8 (a). As shown in Fig. 8 (a), the modification clearly improved the steady state performance(0.5~1.0[sec]). However, the peak over-voltage(1.5[p.u]) during recovery is very high. This is mainly attributable to diminished negative field forcing ability.

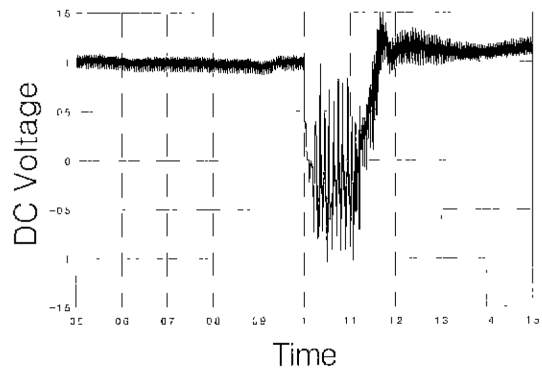


(a) Modified static exciter.

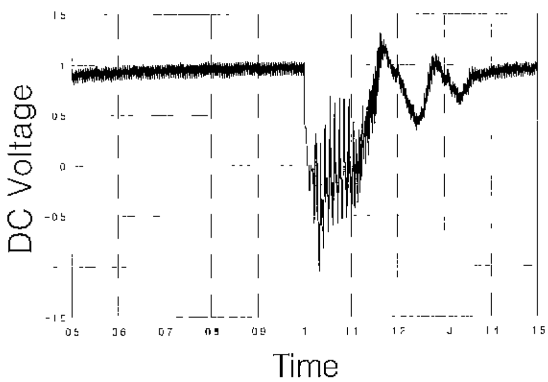


(b) Proposed exciter system

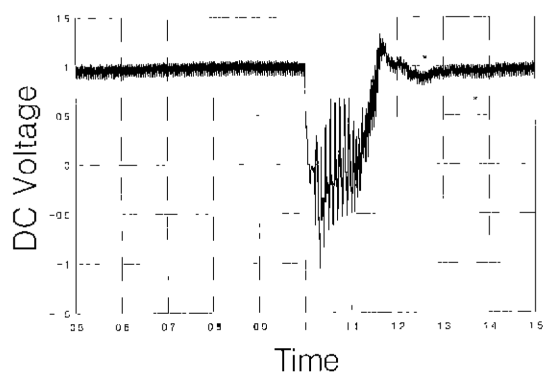
Fig. 8 Modified/Proposed excitation system




(a) Modified static exciter as shown in Fig 7(a)




(b) Proposed static exciter as shown in Fig. 7(b)




(C) Proposed static exciter as shown in Fig 7(b) in the case of $V_R\max = 8$ and $V_R\min = -4$

Fig 9 DC voltage Waveform of HVDC for the proposed static exciter

Another change to the exciter as shown in Fig. 8 (b) was also studied. This change includes an independent power supply and a fully controlled inverter system. The system response is shown for a single phase to ground fault in Fig. 9 (b).

This excitation system shows improved steady state and post fault response. However, in Fig.9 (b), an oscillation due to the rotor dynamics of the synchronous machine is observed. Adjusting the negative ceiling voltage to -4 [p.u] provided a better control of over-voltage as shown in Fig. 9 (c).

## 4. CONCLUSION

Although synchronous compensator improves the system strength and essential in weak HVDC systems, it is important to select proper exciter systems to achieve optimum performance. Static exciter has a faster response compared to the AC rotating type exciter. However static exciter can be less stable than the AC rotating type exciter. By properly adjusting the negative field forcing limits, it is possible to achieve a fast and stable excitation system. Modification to the conventional excitation system included a controlled inverter an independent power supply (battery). The improved performance was verified through digital simulation using electromagnetic transient simulation program EMTDC.

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## NOMENCLATURE

$T_R$: Sensor time constant,

$T_C$: Lead compensator gain,

$T_B$: Lag compensator gain,

$V_R max$: Max. ceiling voltage,

$V_R min$ : Min. ceiling voltage,

$V_g$ : Generator terminal voltage,

$T_A$ : Exciter time constant,

$V_A max$: Max. ceiling voltage of exciter generator,

$V_A min$: Min. ceiling voltage of exciter generator,

$T_{EX}$: Exciter generator time constant,

$K_{EX}$: Exciter generator gain,

$T_{do'}$: D-axis transient time constant,

$T_{gA}$: AC rotating exciter lag compensator,

$E_{FD}$: Exciter output voltage,

$Z_l$: AC line impedance,

$Z_f$: AC filter impedance.

$Z_s$: AC generator impedance,

$\omega_0$: Fundamental frequency of AC network.

$P_d$: DC power,

$\Delta V$: Available generator voltage.

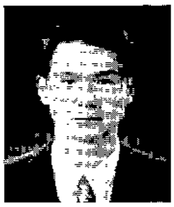
## APPENDIX

### ● CIGRE MODEL PARAMETER

○ HVDC Capacity : 1000[MW]
○ HVDC DC Voltage : 500[kV](per 1 pole)
○ HVDC DC Current : 2000[A]
○ HVDC 1 Pole : 12-pulse Converter
○ HVDC Construction : Biploe
○ Minimum $\gamma$ : 15 [degree]
○ DC line Resistance : 5[$\Omega$]
○ AC network Impedance( $Z_L$) = 52.9[$\Omega$]
○ AC network Voltage : 230[kV]
○ AC/DC TR. Leakage Impedance : 18[%]

○ Filter and Capacitor
-Low Pass Filter : 80[Ω]
-High Pass Filter : 7.5[Ω]
-Fixed Capacit0or : 13.05[Ω]

## 저 자 소 개




**김찬기(金燦起)**
1968년 12월 17일생. 충북 충주 출생. 1991년 서울산업대학교 전기공학과 졸업(학사). 1993년 중앙대학교 대학원 전기공학과 졸업(석사). 1996년 동 대학원 전기공학과 졸업(박사). 1996년-현재 전력연구원 선임연구원.