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5 [KHz] 전압공진형 인버터를 이용한 직렬보상장치 연구

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A study of HFLC series compensator as a power flow controller in an ac power system

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ABSTRACT

The main objective of this paper is to explore the feasibility and potential benefits of HFLC series compensator as a power flow controller in an ac power system. To accomplish this goal, the detailed 5 [KHz] model for EMTP simulation study is developed. Among the issues considered are analysis, tank circuit design, link frequency selection, harmonics and filter requirement, control and damping effect.. The technical evaluation performed in this research can be used in future power network design and operation.

1. INTRODUCTION

High Frequency Link Converter (HFLC) concept was first proposed by P.M. Espelage and B.K. Bose [1]. Due to recent advances in high power semiconductor technology [2], HFLC is now recognized to have great potential for utility level applications. HFLC offers a greater flexibility in controlling network power flows than any other known techniques. Zero voltage switching provides HFLC with lower switching-related losses. The HFLC has four applications based on the topologies of HFLC in an ac power system. One topology among them can work as a series compensator in an ac power system. The objective of this research is to investigate the HFLC as a series compensator in an ac power system.

2. TOPOLOGY OF HFLC SERIES COMPENSATOR

Fig. 1 shows the topology of the HFLC series compensator. The HFLC series compensator has six bidirectional switching devices with reverse blocking capability, a single ungrounded tank circuit, a 60 Hz series-connected transformer and a controller. There can be no real power supply to/from the HFLC series compensator, since the circuit is one-sided. Reactive power flow to/from the converter can be either direction, so the HFLC series compensator can act as a variable series-connected capacitor or reactor.

Fig. 2 shows the phasor diagram corresponding to Fig. 1. The real and reactive power flows in Fig. 1 are described as

$$P_1 = \frac{V_1 V_2 \sin\delta}{X} + \frac{V_1 \Delta V}{X}\cos\frac{\delta}{2} \qquad (1)$$

$$Q_1 = \frac{V_1^2 - V_1 V_2 \cos\delta}{X} + \frac{V_1 \Delta V}{X}\sin\frac{\delta}{2} \qquad (2)$$

The magnitude of the HFLC series compensator output voltage, ΔV, in (1) is controlled to produce the desired amount of series compensation. (1) also explains how the

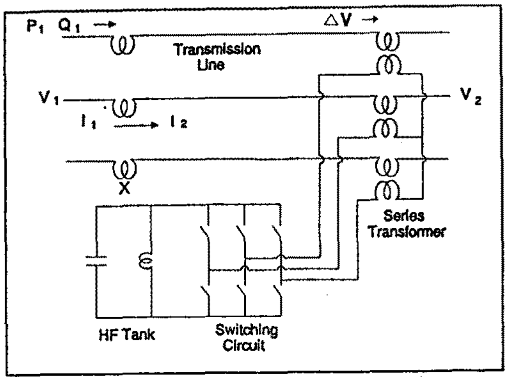

Figure 1. HFLC series compensator connected to a simple ac transmission line system.

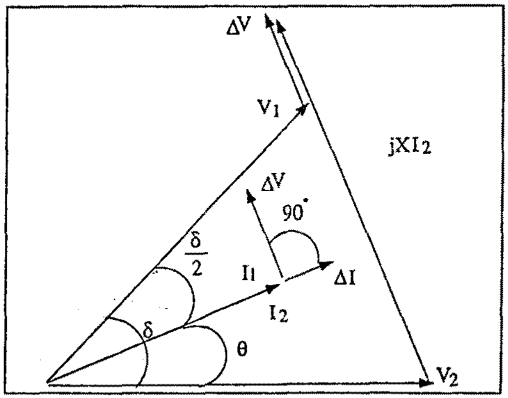

Figure 2. Phasor diagram of the simple ac power system with HFLC series compensator.

HFLC series compensator produces the real power flow even at 0° power angle with the expense of a substantial reactive power of the tank circuit. The reactive power flow in (2) can not be controlled independently. In steady-state, the phase angle of ΔV is slightly less than 90°, to allow for a small amount of energy flow into the tank, in order to compensate for circuit losses.

3. TANK CIRCUIT DESIGN

The selection of link frequency is an important design parameter. The link frequency is approximately determined as

$$f_h \approx \frac{1}{2\pi\sqrt{L_t C_t}} \quad [Hz] \qquad (3)$$

where C_t is a capacitor and L_t is an inductor in the tank circuit. It was especially emphasized that when the frequency ratio, $2f_h/f_s$, between the switching frequency and the reference signal frequency is above 80, the delta modulator has the small rms current distortion below 3% [3]. Therefore the 5 KHz tank circuit can be considered to be a proper link frequency.

In the practical HFLC, the peak value, V_t, of the tank voltage is not constant. A large ripple may cause distortion in the synthesized output. The relationship between the ripple of the tank voltage, ΔV_t, and the capacitance can be expressed as

$$\Delta V_t \approx \frac{I_m}{2\pi_h V_t\ C_t} \qquad (4)$$

where I_m is the magnitude of the line current. (4) shows that ΔV_t can be reduced by a large capacitor or by a high tank voltage. A high tank voltage causes stress on the switching devices. A bigger capacitor requires greater circulating tank current to generate the same magnitude of tank voltage at a given frequency, f_h. Therefore, the capacitor size should be minimized to a size which produces an acceptable ripple in the tank voltage.

4. CONTROLLER DESIGN

Fig. 3 shows a diagram of the controller developed for the HFLC series compensator. Overall control system is a combination of the sub-level controllers such as the CRWPDM controller, the power flow controller, the tank voltage controller and the protector. The upper loop controls the real power for the system by working on the current reference magnitude I_m. The lower loop controls the tank voltage by working on the current phase angle in order to regulate the net energy flow into the tank.

With small disturbance assumption, G_p for power flow control is designed as a second order transfer function system, because a higher order transfer function system can be approximated as a second order transfer function and because the steady-state error of the second order system to a step change is zero. G_p is very important for characterizing a system's response. G_t, K_v controls the internal tank voltage. G_t is also designed as a second order system. However, due to the importance of the tank voltage, G_c should be able to predict a large over shoot ahead of time. The speed of response can easily be selected by adjusting the control gains K_p and K_v.

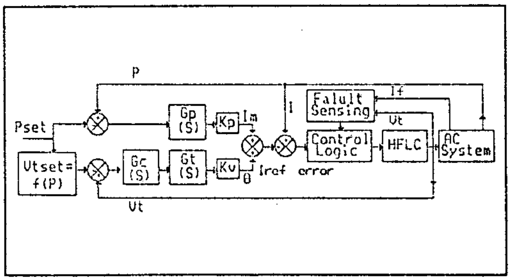

Figure 3. Controller of the HFLC series compensator.

5. EMTP SIMULATION STUDY

Fig. 4 shows the 500[KV], 2000[A] utility system tested in the EMTP simulation study, which interconnects the Southern Company network with the Florida grid. The location of the HFLC series compensator was selected to be in one of the these lines near the Poinsett bus. Since it is basically radial system, the HFLC is useful mainly for increasing power flow during loss of the tie lines or loss of the power generation in the South Florida region and for preventing circulating power between the lines.

Fig 5 shows the 300[KV] tank voltage. The tank voltage changes the peak value at every half cycle. Fig. 6 shows the converter output voltage, ΔV. Fig.7 shows the unfiltered line-to-neutral voltage at the converter output on the right-hand side of the circuit. Although unfiltered, this voltage appears very sinusoidal.

Fig. 8 shows that the voltage harmonics of the unfiltered line-to-neutral voltage at the converter output

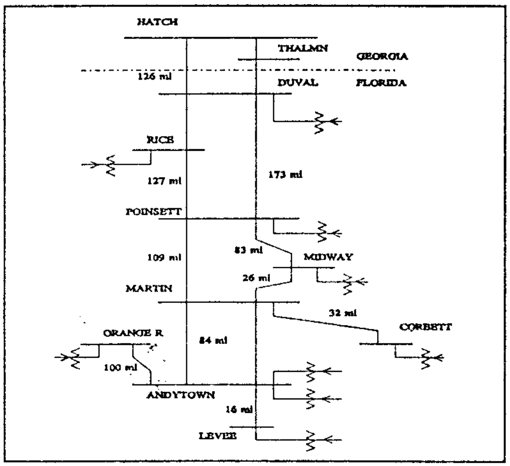

Figure 4. The simplified one line diagram of FP&L 500[KV] system.

are extremely low and occur at the frequencies well above those normally of concern in power systems. Although these high frequency harmonics may be easily and economically filtered, it is possible the system could operate satisfactorily without filters. THD taken out to the 21st harmonic is less than 2%.

Fig 9 shows the power flows of the Duval-to-Poinsett line and the Duval-to-Rice line. When a 300 MW generation unit in the area of South Florida is lost, the power-flow controller initiates a HFLC series compensator to increase the 300 MW real power through the Duval-to-Poinsett line. Due to the existence of closed loop between the Duval bus and the Poinsett bus, however, HFLC series compensator has also the influence on the parallel Duval-to-Poinsett line through the Rice bus. Fig. 10 shows the tank voltage of the HFLC series compensator under the same conditions depicted in Fig.9. The tank voltage has transient period due to the unbalanced power between the Duval bus and the Poinsett bus. The peak voltage reference was also shown in Fig. 10. The initial setting of tank voltage was 200 KV, but it is not enough to increase 300 MW through Duval to Poinsett line so the tank voltage was increased to 300 KV. As mentioned earlier, the tank voltage is kept at the minimum value to reduce the switching stress and loss.

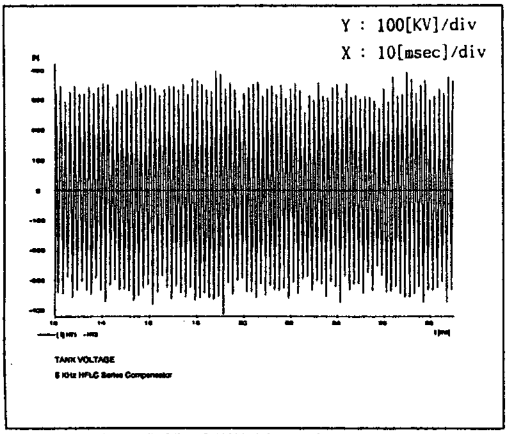

Figure 5. The 5 [KHz] internal tank voltage.

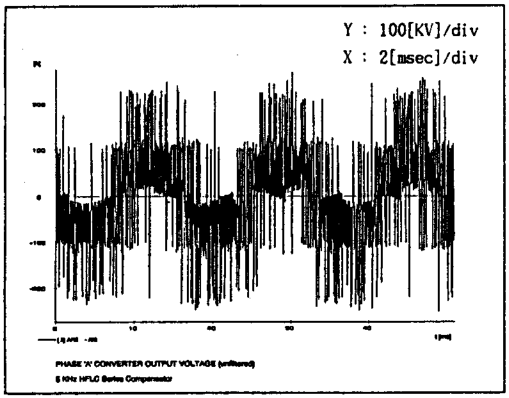

Figure 6. The synthesized output voltage.

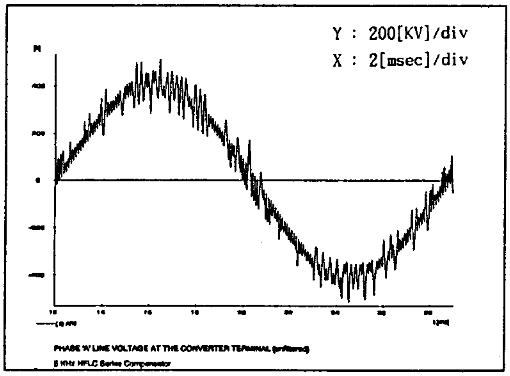

Figure 7. The synthesized line voltage.

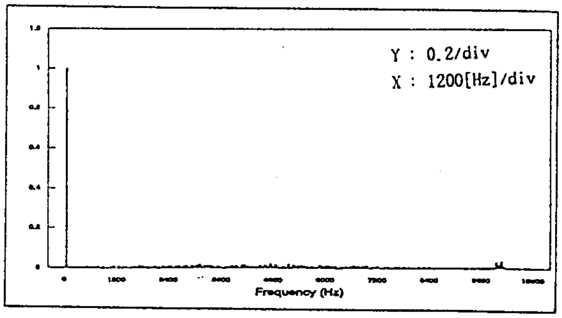

Figure 8. Frequency spectrum of the synthesized line voltage.

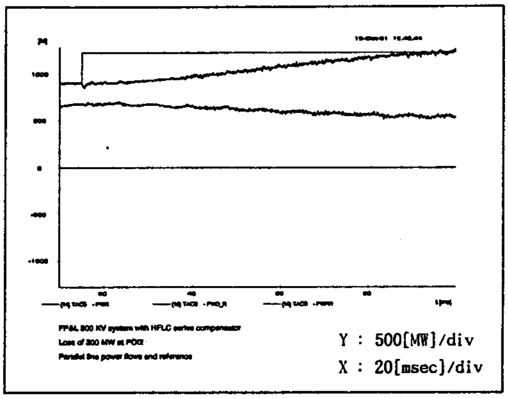

Figure 9. Real power flow of Duval-to-Poinsett and Duval-to-Rice lines and the reference.

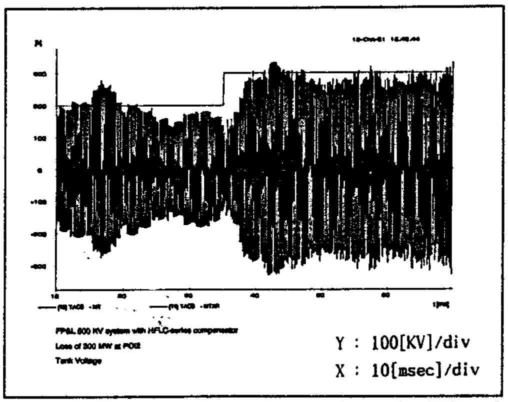

Figure 10. Tank voltage response and the reference for the loss of 300 MW unit.

Fig. 10 shows the tank voltage decreasing at beginning of the step change in power flow. This is because a fast transient power flow increase requires a temporary depletion of tank energy. The response speed of the power flow control must be limited by the control system to prevent a transient collapse of the tank voltage.

Fig. 11 shows the result of 3ϕ line fault at the Duval bus without the HFLC series compensator. The 3ϕ line fault occurs at 16.7 msec and continues to the end of the simulation. Fig. 12 shows that the HFLC series compensator is used to damp out the oscillatory power swing. Fig. 13 shows the tank voltage of the HFLC series compensator under the same conditions of Fig. 12. A big unbalance of power flow exists in the FP&L system after the fault occurs. It induces the overvoltage in the tank circuit because it instantaneously absorbs the unbalance of power flow. Deadband control is used for the protection of the HFLC. After the high tank voltage has disappeared, the HFLC damps the oscillatory power swing out in a shorter period than it normally would without the HFLC.

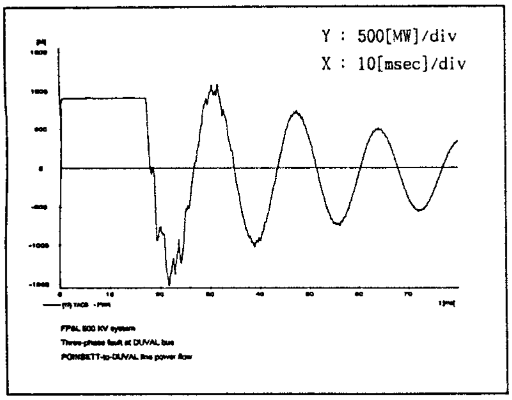

Figure 11. The Duval-to-Poinsett line power flow during three-phase faults at Duval bus without HFLC series compensator.

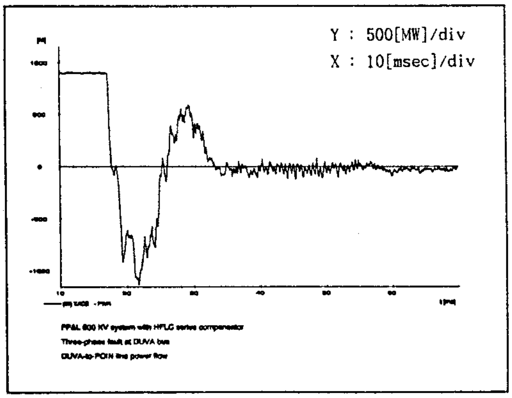

Figure 12. The Duval-to-Poinsett line power flow during three-phase faults at Duval bus with HFLC series compensator.

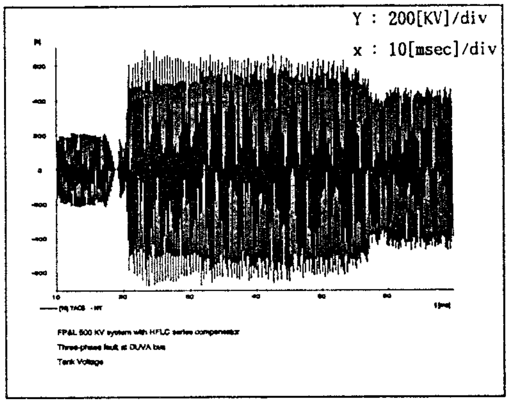

Figure 13. Tank voltage response for three-phase faults at Duval bus.

6. CONCLUSION

The EMTP simulation study of the HFLC series compensator in a power system shows that the 5 [KHz] HFLC series compensator can be used to improve the performance of the ac power system. The circuit synthesizes the required output smoothly, quickly and accurately. The designed controller works properly in steady-state and transient situation. However, the one installation of the circuit in the radial system is not enough to prevent the loop power flow. The models used in this simulation research are suitable only for relatively short-term studies, because of large computing time requirements. However much can be learned about the overall performance of the HFLC series compensator as a power flow controller in a power system.

7. REFERENCES

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[2] L. Gyugyi,"Solid-State Control of AC Power Transmission," EPRI workshop on the Future in High Voltage Transmission, Cincinnati, Ohio, November 1990.

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