Improvement of Voltage Stability by the Advanced High Side Voltage Control Regulator

Hitomi Kitamura, Masaru Shimomura (Member)

Mitsubishi Electric Corporation
Kobe, Japan

John Paserba (Member)

Mitsubishi Electric Power Products, Inc.
Warrendale, Pennsylvania, USA

Abstract: An advanced High Side Voltage Control (HSVC) regulator that can improve power system voltage stability by adding supplemental control to conventional generator excitation system control has been developed. This paper describes the principles, characteristics, and advantages of applying advanced HSVC in comparison with a conventional automatic voltage regulator (AVR) or a static var compensator. When applying the advanced HSVC, a high side voltage of a step-up transformer can be controlled to a set value and maintained to a higher value than with conventional excitation systems. This advanced HSVC is realized without any feedback signal from the high voltage side of a step-up transformer (i.e., no high-side voltage measurement required). Stable parallel operation among adjacent generators is also possible. In addition, with an adequate phase compensating function added to the advanced HSVC, oscillatory stability can also be improved.

Keywords: Secondary Voltage Control, Automatic Voltage Regulator (AVR), Static Var Compensator, Line Drop Compensator (LDC), Excitation System, Voltage Stability, Oscillatory Stability.

I. INTRODUCTION

Voltage instability of power systems is becoming a more serious problem with the ever-increasing utilization and higher loading of existing transmission systems. Various countermeasures, i.e., synchronous condensers, shunt capacitors, static var compensators, etc., have been increasingly utilized.

Other effective alternatives, such as the line drop compensator (LDC) that compensates the voltage drop by a reactive current, or the power system voltage regulator (PSVR) that uses a high side voltage as a feedback signal [1], have also been applied as control methods of the high side voltage of a step-up transformer (S.Tr) via a generator excitation system.

The advanced High Side Voltage Control (HSVC) regulator that controls the high side voltage of a step-up transformer has been developed with no requirement for any direct feedback signal (i.e., measurement) from the high voltage side of a step-up transformer. Though the control principle of the advanced HSVC is similar to that of the LDC, the advanced HSVC is superior to the traditional methods with respect to control performance, reliability, and economy, as described in this paper.

II. PRINCIPLE & CHARACTERISTICS of HSVC

The configuration of the advanced HSVC is shown in Figure 1. The basic principle of the advanced HSVC on a simple power system, shown in Figure 2, is as follows.

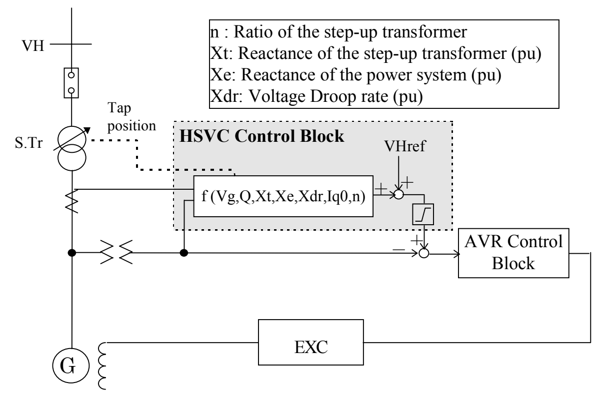


Figure 1. Construction of HSVC control system

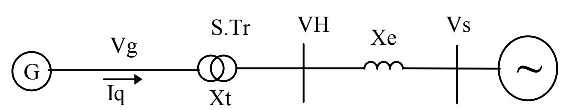


Figure 2. Simple power system

1) Basic Function

With a target setting value of the high side voltage (VHref), the generator terminal voltage (Vg), i.e., the low side voltage, is controlled to be:

$$Vg = VHref + (Xt - Xdr)\, Iq \tag{1}$$

Where, $Iq = Q / Vg$. On this condition, the resultant high side voltage (VH) becomes,

$$VH = VHref - Xdr\, Iq \tag{2}$$

This characteristic can be expressed as shown in Figure 3.

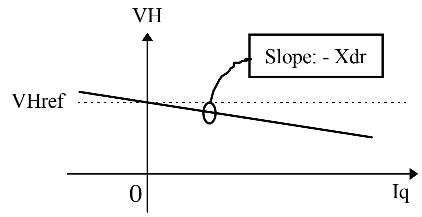


Figure 3. Characteristics of HSVC

In words, for a target of VHref, the VH can be controlled to only drop for part of Xdr. This Xdr is necessary for stable parallel operation among multiple generators.

2) Reactive Current Compensation Function

To equal the VH with VHref at the specified reactive current (Iq0), a supplemental control can be adopted by using Iq0. The VH at large reactive current can be kept to a higher value by this function. The Vg is controlled to be:

$$Vg = VHref + Xt\, Iq - Xdr\,(Iq - Iq0) \quad (3)$$

and the VH becomes,

$$VH = VHref - Xdr\,(Iq - Iq0) \quad (4)$$

This characteristics can be expressed as shown in Figure 4.

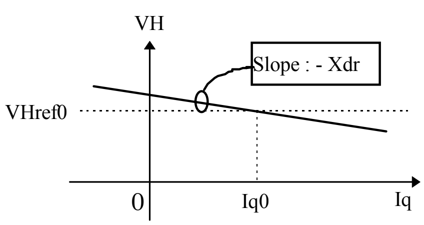


Figure 4. Characteristics of reactive current compensation function

3) Reactive Current Compensation Function by Xe

This function is used to follow Iq0 automatically corresponding to the variation of the VHref.

For an original setting value VHref0 and an external reactance Xe, a change of the reactive current (ΔIq0) by a new setting value VHref is approximately given as (5).

$$\Delta Iq0 = (VHref - VHref0)/Xe \quad (5)$$

Therefore, this function can be realized by adding (5) to Iq0 of (3) and (4).

4) Compensation Function of the Droop Rate Corresponding to the Variation of the Tap Position of the Step-Up Transformer

When the Vg is controlled by the advanced HSVC, the Vg may be generally maintained higher than its rated voltage in order to keep the VH to a constant value. On the other hand, the continuous allowable Vg is generally up to 5% of the rated voltage. If the Vg is near this maximum voltage in a steady state condition, the improving effect of the voltage stability by the advanced HSVC is reduced by this limitation. Therefore, in the case of a step-up transformer with LTC, the cooperative control between the advanced HSVC and the tap position control can increase the ability of the advanced HSVC by way of keeping the Vg to around the rated voltage in steady state condition. The following division of roles between the advanced HSVC and the tap position control is a suitable solution to improve the voltage stability.

Control	Function
HSVC	Controls VH to VHref
Tap control	Controls Vg to approximately the rated voltage

However, the droop rate changes according to the variation of the voltage ratio and the reactance of step-up transformer (Xt) by controlling the tap position. As a result, the parallel operation among adjacent generators may become difficult due to an unbalance of reactive power on each generator, which is caused by discrepancy of tap position of each step-up transformer. For preventing this condition, the compensation function that keeps the droop rate constant corresponding to the tap position can be added to the HSVC. In the case that both a change of the voltage ratio and the reactance by a change of the tap position is the same value (n), the basic control function is changed from (1) to (6).

$$Vg = VHref/n + (Xt - Xdr/n)\, Iq \quad (6)$$

The resultant VH becomes the same as (2).

As mentioned above, although this characteristic is the same as with the application of LDC, the advanced HSVC has the following superior features.

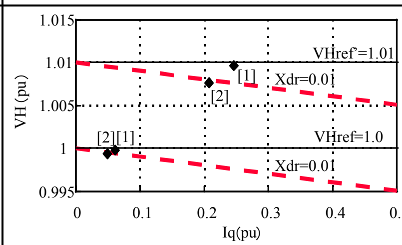
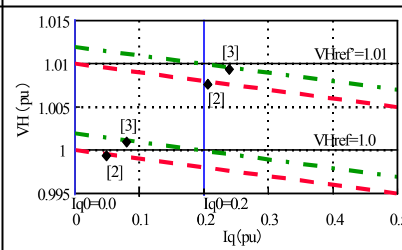
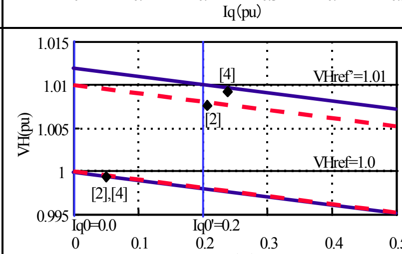
- The VHref can be directly set to a desired value from local and/or remote location. Accordingly, the cooperating control of the power system voltage among multiple generators and/or substations is possible.
- A feedback signal (i.e. measurement) of a high side voltage is not required.
- The following optional functions can be added to the HSVC:

- Reactive current compensation function
- Reactive current compensation function by Xe
- Compensation function of the droop rate corresponding to the variation of the tap position of the step-up transformer.
- A phase compensation function can be added to further improve stability by modifying the response characteristics of the HSVC control loop.
- The oscillatory stability of a power system can be improved by adding an adequate phase compensation function.

The performance of the HSVC described in the equations above was verified by simulation analysis of a step-change of the VHref from 1.0pu to 1.01pu on a simple power system. These results are shown in Figure 5 and Figure 6.

Figure 5 shows each resultant characteristic that is plotted according to the simulation results before and after a step-change. Where each line shows the theoretical characteristic.

The case A shows the droop characteristics of HSVC that is represented by (2). In this figure, theoretical and simulated results are obtained for variations in VHref and Xdr. These resultant points can be shown to fit each theoretical line very well.

Case &Condition	Characteristics
A. Study of effect of the droop rate Xdr Common Condition Iq0=0.0pu Parameter : Xdr(pu) [1] Xdr=0.0 [2] Xdr=0.01	
B. Study of effects of Iqo function Common Condition Xdr=0.01 pu Parameter : Iq0(pu) [2] Iq0=0.0 [3] Iq0=0.2	
C. Study of effects of Iqo compensation function by Xe Common Condition Xdr=0.01pu Iq0=0.0pu Parameter : compensation function [2] off [4] on(Xe=0.05pu)	

Initial Condition : P1=0.9pu, Q1=0.04pu, VHref=1pu

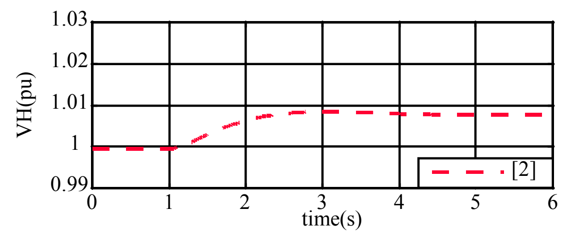
Step : Δ VHref=0.01pu, 100MVA base

Figure 5. Verification result of HSVC function

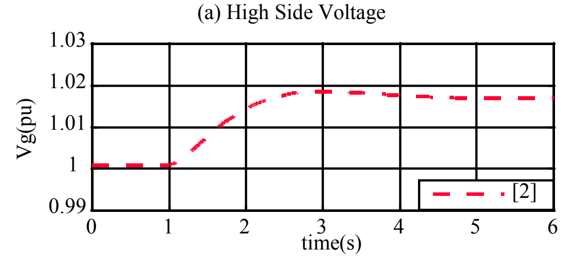
The case B shows the characteristic of Iq0 function that is represented by (3). In this figure, theoretical and simulated results are obtained for variations in VHref and Iq0. In the case of Iq=Iq0, the VH is the nearer value to the VHref. Therefore, if the Iq0 is set to the actual value on the normal operation condition, the VH can be controlled to the VHref.

The case C shows the characteristic of the Iq0 compensation function by Xe. In this figure, theoretical and simulated results are obtained for variations in VHref and without or with this function. These results show that the VH is controlled near the value of VHref both before and after the change of VHref, according to the theory.

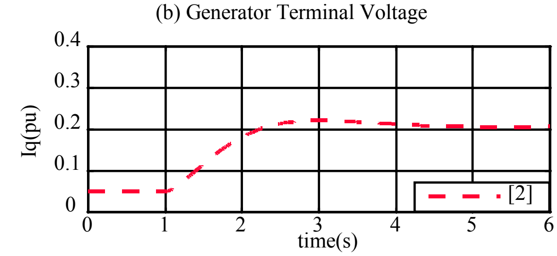
Figure 6 shows the response characteristics of the advanced HSVC in the case of [2]. The VH reaches the VHref at about 1.5 sec. and is also controlled smoothly and stably.



(a) High Side Voltage



(b) Generator Terminal Voltage



(c) Generator Reactive Current

Figure 6. Response characteristics of the HSVC

III. IMPROVEMENT of VOLTAGE STABILITY

The improving effect on the voltage stability of a power system by the advanced HSVC was estimated by P-V characteristics [2, 3]. Figure 7 shows a model of a simple power system. The resultant P-V characteristics by applying a static var compensator and the advanced HSVC are respectively shown as Figures 8(a) and 8(b).

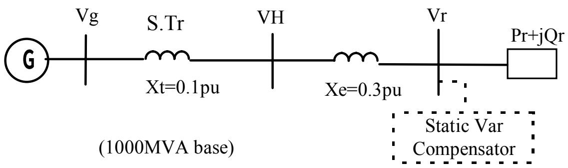
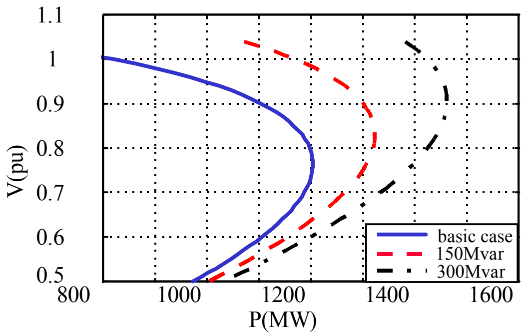
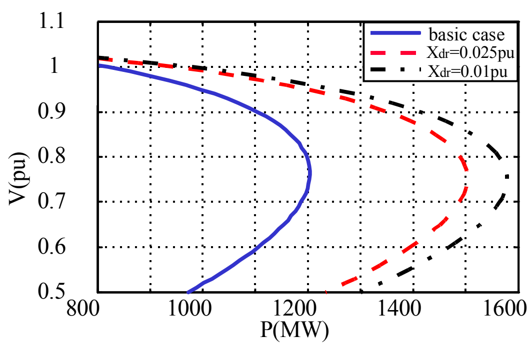


Figure 7. Simple model of a single machine and one load



(a) P-V curve (static var compensator)



(b) P-V curve (HSVC)

Figure 8. P-V characteristics

For the static var compensator, the allowable sending end power increases according to larger capacities of installed static var compensator, but the "nose" voltage tends to go up. On the other hand, for the advanced HSVC, the allowable sending end power increases according to a decrease in the droop rate and the nose voltage tend to go down. In other words, the advanced HSVC can also improve the system voltage characteristics by way of both pushing out the "nose" of the curve and not getting near the normal operating voltage of the power system. Moreover, since the advanced HSVC can be installed on all generators, including already installed facilities, the existing capability of power plants can effectively be put to practical use for voltage stability. Therefore, the advanced HSVC is also superior on economy.

IV. IMPROVING EFFECTS OF OSCILLATORY STABILITY

The improving effect on oscillatory stability by the advanced HSVC can be treated via the extended DeMello/Concordia model [4] shown in Figure 9. Parameters K7 and K8 can be respectively calculated by (7) and (8). The simplified model can be expressed as shown in Figure 10.

$$K_7 = \frac{-X_d' i_{do} + V_{qo}}{X_d' + X_e} V_b \sin\delta_o - \frac{X_q i_{qo} + V_{do}}{X_q + X_e} V_b \cos\delta_o \quad (7)$$

$$K_8 = \frac{X_e i_{do} + V_{qo}}{X_d' + X_e} \quad (8)$$

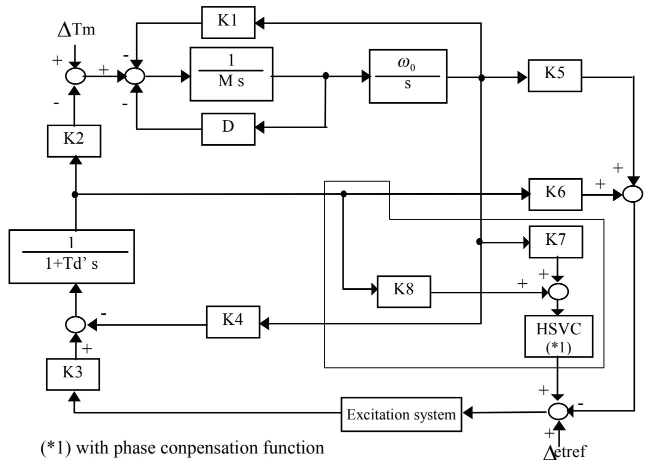


Figure 9. Extended DeMello/Concordia model

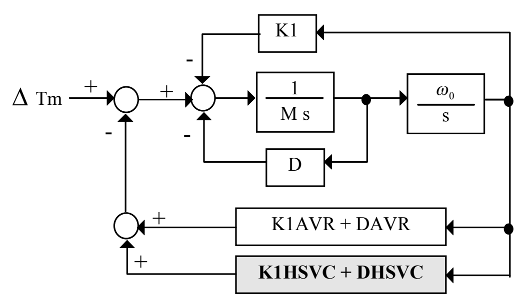
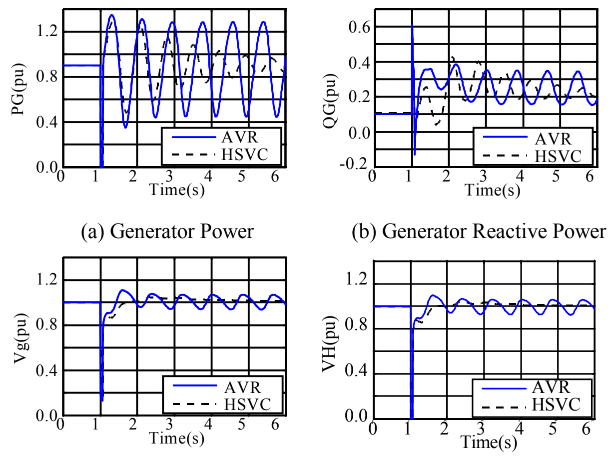


Figure 10. Simplified model

K1AVR and DAVR are the factors of the synchronizing torque and the damping torque by the excitation system, respectively. Similarly, K1HSVC and DHSVC are the factors of the synchronizing torque and the damping torque by the HSVC, respectively. Accordingly, if a phase compensation function is added such that DHSVC becomes positive, then this means that damping, D, is added and thus the oscillatory stability of the power system can be improved. Figure 11 shows the simulation result in the case of a three-phase fault on the high voltage side of step-up transformer with the advanced HSVC equipped with a suitable phase compensation function. Where, in both cases of AVR and HSVC, a conventional PSS is not applied. This result shows a good mitigating effect of power system oscillations.



(a) Generator Power (b) Generator Reactive Power

(c) Generator Terminal Voltage (d) High Side Voltage

Condition : xt=0.05pu, Xe=0.2pu, 100MVA base

Figure 11. Suppressing effect of power oscillation

V. PERFORMANCE ON PARALLEL OPERATION

The performances for two cases of the parallel operation of two generators G1/G2 and four generators G1/G4 on the power system shown in Figure 12 were studied.

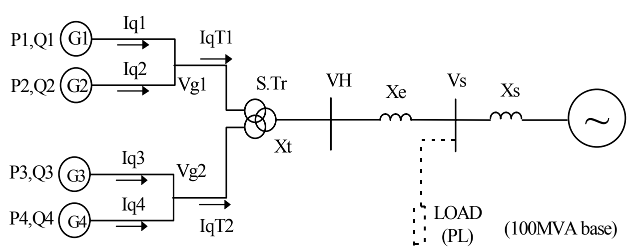


Figure 12. Four machines model for studying the parallel operation

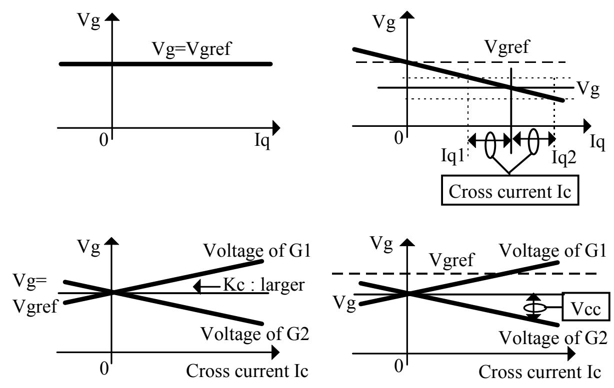
For this study, the advanced cross current suppression function is added to suppress the reactive cross current between the generators directly connected on the low voltage side of the step-up transformer. Here, it is between G1 and G2 and between G3 and G4. The conventional cross current compensating function that uses a load current of each generator may have a negative impact on voltage stability, because Vg would decrease as reactive power increases. This compensating signal (Vcc) is:

$$Vcc = Xc\ Iq \tag{9}$$

Because of this reason, the advanced method that reduces the cross current by the deviation signal between generators is adopted. This compensating signal (Vac) for G1 is shown in (10).

$$Vac = Kc\ (Iq2 - Iq1) \tag{10}$$

By increasing the suppression gain of cross current Kc, the cross current can be reduced and the deviation between generators becomes smaller. Accordingly, the Vg is not influenced by the reactive current of each generator and is kept to constant. These characteristics of the conventional method and the advanced method are compared in Figure 13.



(a) Advanced method (b) Conventional method

Figure 13. Characteristics of cross current suppression function

Figure 14 and Figure 15 show respectively the simulation results for the step response (=0.01PU) of VHref on the parallel operation of two generators and four generators. The results on two generators operation is as follows and mainly verifies the characteristics of the advanced cross current suppression function.

(a) The VH follows against a step of the VHref within several seconds and is smoothly controlled without fluctuation. The resultant VH fits the theoretical value.
(b) Even if the Vg detected by each AVR is different, the VH can be stably controlled according to the VHref.
(c) In spite of a discrepancy of each AVR gain, the VH can be controlled according to the VHref except for a slower response of Iq2 by the lower AVR gain.
(d) In spite of a discrepancy of each AVR response characteristic, the VH can be controlled to the VHref except for a slower response and increasing an overshoot of the G2.

(e) In spite of a discrepancy of operation mode, the VH can be stably controlled. As the Xc becomes large, a deviation of Iq becomes small.

(f) Even if the step signal to G2 AVR is delayed, the VH can be stably controlled according to the VHref.

The results on four generators operation is also as follows and mainly verifies the characteristics between generator groups, G1/G2 and G3/G4.

(a) The VH follows against a step of the VHref within several seconds and is smoothly controlled without fluctuation. The resultant VH fits the theoretical value.

(b) Even if the Vg detected by each AVR is different, the VH can be stably controlled according to the VHref except for a discrepancy of Iq and Vg between the groups.

(c) In spite of a discrepancy of each AVR gain, the VH can be controlled according to the VHref except for a slower response of Iq3/Iq4 by the lower AVR gain.

(d) In spite of a discrepancy of each AVR response characteristic, the VH can be controlled to the VHref except for a slower response and increasing the overshoot of G3/G4.

(e) In spite of a discrepancy of operation mode, the VH can be stably controlled. As the Xdr becomes large, a deviation of Iq becomes small.

(f) Even if the step signal to G3/G4 AVR is delayed, the VH can be stably controlled according to the VHref.

VI. CONCLUSIONS

The performance of the various functions of advanced HSVC based on a simple power system were introduced. The simulation results were in agreement in every respect according to theoretical expectation and it was confirmed that the advanced HSVC could be put to practical use.

For future development steps, the following studies will be continued to further improve the functions and benefits of the advanced HSVC.

- Analysis and brush-up of the improving effects of the voltage stability and the oscillatory stability on the multi-machines model.
- Study of the control method and the improving effects for a transient stability by the advanced HSVC.

VII. REFERENCE

[1] T. Michigami, N. Onizuka, S. Kitamura, “Development of Advanced Generator Excitation Control Regulator (PSVR) for Improving Voltage Stability of a Bulk Power Transmission System,” The Institute of Electrical Engineers of Japan, Vol. 110-B, No. 11, November 1990, pp. 887-894

[2] C. Taylor, Power System Voltage Stability, McGraw-Hill, Inc., 1994.

[3] P. Kundur, Power System Stability and Control, McGraw-Hill, Inc., 1994, pp. 216-220.

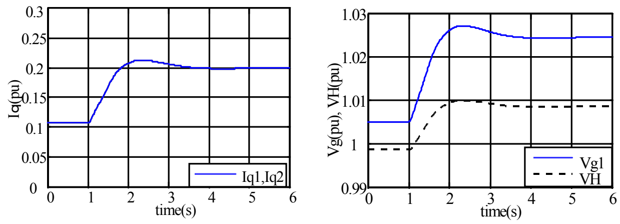
[4] F. P. De Mello and C. Concordia, “Concepts of Synchronous Machine Stability as Affected by Excitation Control,” IEEE Transactions on Power Apparatus and Systems, Vol. PAS-88, Apr. 1969, pp. 316-329.

VIII. BIOGRAPHIES

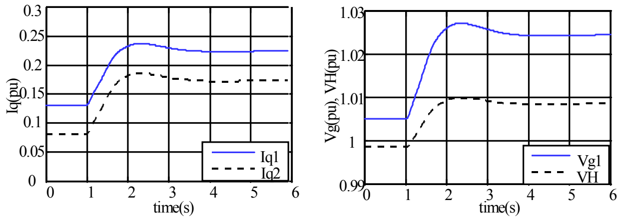
Hitomi Kitamura received a M.S. degree in Electrical Engineering from Kansai University in 1998. Since 1998, she has been with the Mitsubishi Electric Corporation in Kobe, Japan, and is working for the design and the development of excitation system and the analysis of power system stability.

Masaru Shimomura received a B.S. degree in Electrical Engineering from Kyusyu University in 1970. Since 1970, he has been with the Mitsubishi Electric Corporation in Kobe, Japan, and has been mainly developing the excitation control system. His present main activity is management of electrical engineering for control system of power plant.

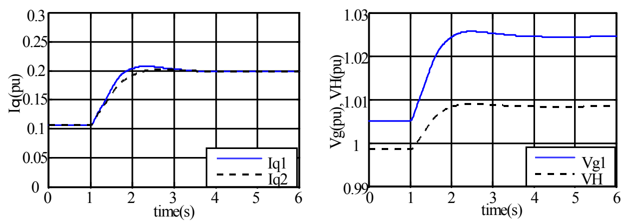
John Paserba earned his BEE (87) from Gannon University, Erie, PA., and his ME (88) from RPI, Troy, NY. Mr. Paserba worked in GE’s Power Systems Energy Consulting Department for over 10 years before joining Mitsubishi Electric Power Products Inc. (MEPPI) in 1998. He is the Chairman for the IEEE PES Power System Stability Subcommittee and was the Chairman of CIGRE Task Force 38.01.07 on Control of Power System Oscillations. He is also a member of the Editorial Board for the IEEE PES Transactions on Power Systems.



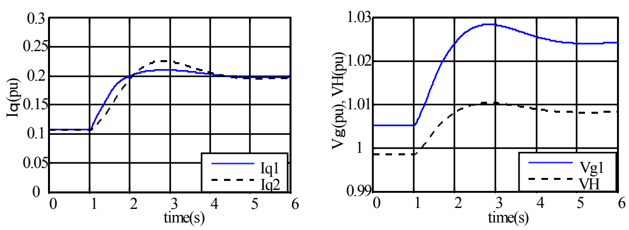
(a)Basic case



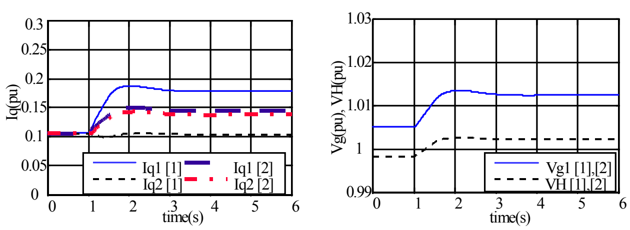
[G1-Vg : G2-Vg=0.995 : 1.005]
(b)Discrepancy of AVR feedback voltage



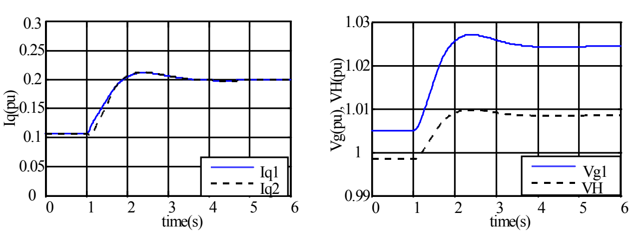
[G1-K : G2-K = 1 : 0.5]
(c)Discrepancy of AVR gain



[G1- ω c : G2- ω c= 1 : 0.5(ω c:cross over frequency)]
(d)Discrepancy of AVR response characteristics

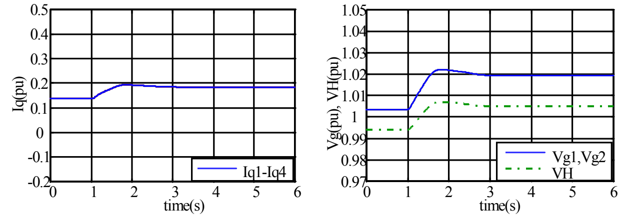


[G1:HSVC, G2:AVR Xc(pu):[1] Xc=0.1 [2] Xc=1.0]
(e)Discrepancy of operation mode

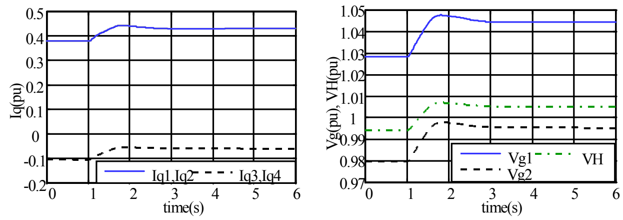


[Timing for change of VHref for G2 is 0.1s later than for G1.]
(f)Discrepancy of timing for change of VHref

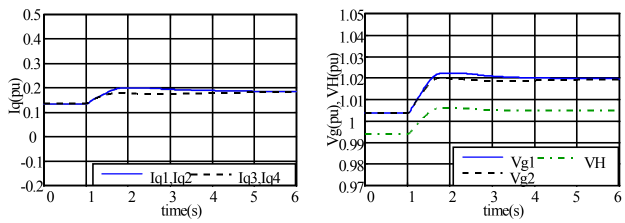
Figure 14. Performance for two generators operation



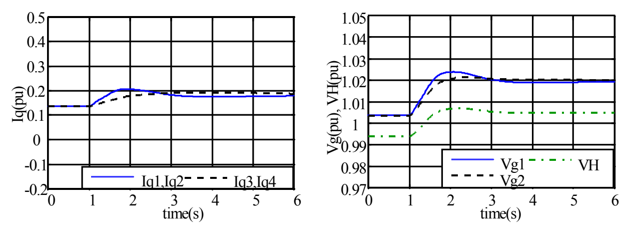
(a)Basic case



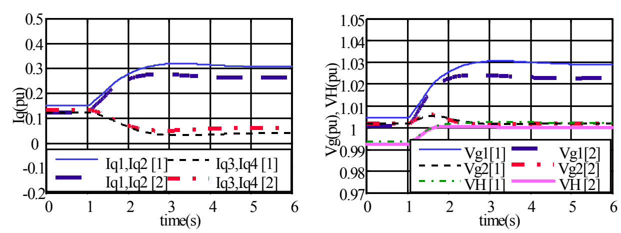
[G1/2-Vg:G3/4-Vg=0.995 : 1.005]
(b)Discrepancy of AVR feedback voltage



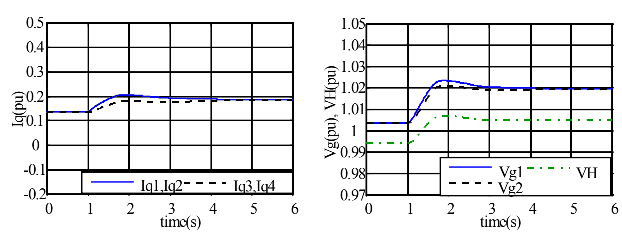
[G1/2-K:G3/4-K = 1 : 0.5]
(c)Discrepancy of AVR gain



[G1/2- ω c:G3/4- ω c= 1 : 0.5 ω c:cross over frequency]
(d)Discrepancy of AVR response characteristics



[G1/2:HSVC,G3/4:AVR Xdr(pu) : [1] Xdr=0.01 [2] Xdr=0.025]
(e)Discrepancy of operation mode



[Timing for change of VHref for G3/4 is 0.1s later than for G1/2.]
(f)Discrepancy of timing for change of VHref

Figure 15. Performance for four generators operation