International Journal of Control and Automation
Vol. 9, No. 7 (2016), pp.169-178
http//dx.doi.org/10.14257/ijca.2016.9.7.16

Implementation and Application of Voltage Management System to Physical Power System for Stable and Robust Operation

Seung-Mook Baek[1] and Hee-Jin Lee[2*]

[1]*Division of Electrical, Electronic and Control Engineering, Kongju National University, Cheonan, Chungnam, South Korea*
[2]*Department of Electronic Engineering, Kumoh National Institute of Technology, Gumi, Gyeongbuk, South Korea*
[1]*smbaek@kongju.ac.kr*, [2]*jinlee@kumoh.ac.kr*

Abstract

The paper describes implementation and application of voltage management system (VMS) to a physical power system for bringing stable and robust operation. The VMS has a role of balancing reactive power generation of the generators, which are controlled by the VMS. The VMS consists of continuous voltage controller (CVC) and discrete voltage controller (DVC). Those are used to maintain the system voltage within stable range. Especially, the CVC induces a supplementary signal to automatic voltage regulator (AVR) to balance reactive power generation of all involved generators. In the paper, the physical application of the VMS is described and the important considerations are introduced. Also, the paper shows the results of the stable application of the VMS.

Keywords: *Automatic voltage regulator, physical system application, reactive power generation, secondary voltage controller, voltage management system*

1. Introduction

As modern power system becomes more complicated, large, and entangled, voltage stability problem has recently been attracted considerable attention for power system stability research. Since realizing the importance of voltage stability, various voltage control schemes have been proposed [1]-[7]. In particular, the secondary voltage regulation based on the hierarchical control system has been introduced in several European countries. The hierarchical system consists of three-level structure such as primary voltage regulation (PVR), secondary voltage controller (SVC), and tertiary voltage regulation (TVR). Those controllers take charge of control actions for voltage stability in the different time period [8]-[9].

In South Korea, the voltage management system (VMS) has been developed and installed in physical power system since 2009. The target power system was Jeju Island power system. The goal of the VMS is to balance reactive power generation of the generators in Jeju Island and to maintain the system voltages within stable range. The control concept of the VMS is from the secondary voltage controller (SVC) in [8]-[9]. The basic operation and control method are similar to the SVC. However, the VMS has one more function which is a discrete voltage controller (DVC). That is the difference between the VMS and the SVC. Actually, the VMS has two operation functions, which are a continuous voltage controller (CVC) and the DVC. The CVC are very similar to the SVC and the DVC computes the reactive power demand and instructs in or out of shunt capacitors in the system. With two control schemes, the system voltage can be

* Corresponding author is with the Department of Electronic Engineering, Kumoh National Institute of Technology, Gumi, 39177, Korea. (Corresponding author to provide phone: +82-54-478-7437; e-mail: jinlee@kumoh.ac.kr)

ISSN: 2005-4297 IJCA

maintained within the stable range and the reactive power generation of the generators and shunt capacitors is balanced for each source to secure enough reactive power reserves.

On the other hand, the parameter selection of the VMS is very important issue because the VMS has two integral controllers. In [2], the method to compute the appropriate values of the parameters is introduced. However, it is not easy to compute the parameters from real system status and there are many important considerations for real field application of the VMS. The paper will introduce the considerations and the method to select the parameter values in real field application. Also, the results are presented with field examination in Jeju Island power system.

The paper is organized as follows: Section 2 presents a summary of configuration of VMS. Then, the parameter selection method based on sensitivity analysis is described in Section 3 and hence section 4 describes the real-time simulation to verify the operation performance of the VMS. Section 5 shows the performances of the field application of the VMS. Finally, the conclusions are given in Section 6.

2. Configuration of Voltage Management System

As shown in Figure 1, Jeju power system has around thirteen 154 kV buses. Also, the power system is connected to the main land power system in South Korea with three HVDC lines. The HVDC lines supply insufficient electric power of the Jeju Island. Pilot bus is a target bus to be controlled by the VMS in order to maintain the system voltage constant. There are four main generators which are controlled by the VMS. Two generators are located in Northern site and the others are located in Southern site in Jeju Island. The energy management system (EMS) and the VMS server are installed in the middle of the Island. In this site, all control signals are sent to the generators via UDP and TCP/IP communication cables [8]-[9].

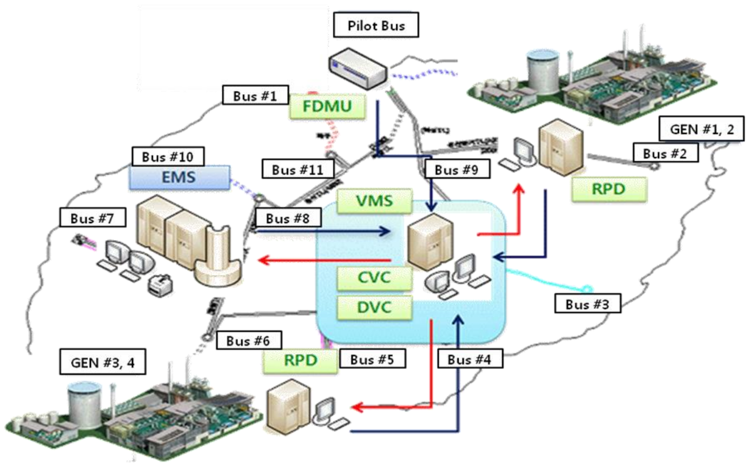

Figure 1. Configuration of VMS in Jeju Island.

The VMS control system has two operation functions, which are the CVC and the DVC. And, the paper focuses on only CVC controller. Figure 2 shows the block diagram of the CVC system. There are two integral controllers and hence the parameter selection is very important issue to prevent from mutual oscillation phenomenon. Therefore, there are several main considerations in order to apply the VMS to physical system. The first is to select appropriate parameter selection. In [2], a method to select the parameters are given and the names of parameters are written in Figure 2. X_t is transformer reactance between generator and pilot bus; X_{eq} is equivanlent reactance; Q_g is reactive power generation of the involved generator K_{psc} and K_{isc} are gains of PI controllers. However, the system parameters cannot be computed accurately in various operation conditions. Therefore, parameter tuning method by sensitivity analysis in physical test is more suitable [8].

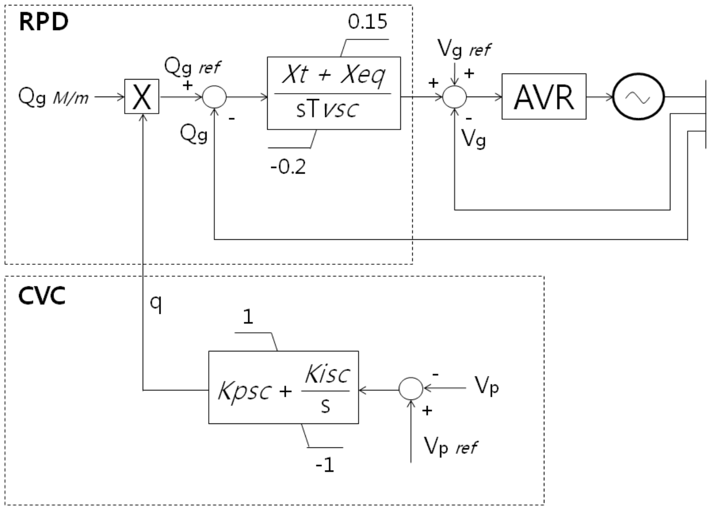

Figure 2. Control Structure of the General SVC.

As shown in Figure 2, the VMS consists of three operation level hierarchically. In the highest level, the set point control (SPC) for the desired voltage value of the pilot bus is computed by solving various problems such as minimizing power loss or maximizing stability margin. The operator can choose any optimization mode for his wish [8].

As mentioned before, the CVC falls into the category of the secondary voltage controller. Therefore, the control strategy in the CVC consists of two parts as shown in Figure 2. The first part follows a proportional-integral (PI) control part [8].

$$
\begin{aligned}
&e_r(t) = V_{pref}(t) - V_p(t) \\
&Q_g\%(t) = k_{psc} \cdot e_r(t) + k_{isc} \cdot \int_0^t e_r(t)dt
\end{aligned}
\tag{1}
$$

where $V_p(t)$ represents the voltage of pilot bus at time *t*; $V_{pref}(t)$ is the voltage reference at time *t* derived from the SPC; $Q_g\%(t)$ is the reactive power to be generated in each RPD; k_{psc} and k_{isc} are proportional and integral gains respectively in the CVC.

In this scheme, the reactive power levels should be generated in each RPD and sent to the RPD controller. The second part follows the integral (I) structure called RPD.

$$
\begin{aligned}
&e_q(t) = Q_{gref}(t) - Q_g(t) \\
&Q_{gref}(t) = Q_g\%(t) \cdot Q_{g\_M/m} \\
&\Delta V_g(t) = k_{ir} \cdot \int_0^t e_q(t)dt
\end{aligned}
\tag{2}
$$

where $Q_g(t)$ represents the reactive power of each generator at time *t*; $Q_{gref}(t)$ is the reactive power reference at time t calculated from Eq. (4); $Q_{g\_M/m}$ is the reactive power upper and lower limits of each generator; k_{ir} means the integral gain in the RPD in Figure 2.

3. Parameter Selection Method by Sensitivity Analysis

As mentioned before, the parameters of the VMS can be computed with system parameters like in [10]-[15]. However, the computed parameters cannot guarantee the stable performances in field application. That is because the system parameters are not accurate due to structural variation of physical system or variation of operation point. Therefore, it would be good if the parameters obtained from [2] are regarded as initial value for starting the applications of VMS to the physical system. Then, the parameters need to be tuned based on the sensitivity analysis in Eqs. (3) and (4). By those equations, we can gauss how much reactive power generation will be changed as the small input signal change. With this relationship, we can tune the value of the parameters of the VMS.

$$\begin{aligned}
\Delta V_G &= \frac{X_t + X_{eq}}{T_{vsc}} Q_{G_M/m} \cdot k_{psc} \cdot e_r(t) + \\
&\quad \frac{X_t + X_{eq}}{T_{vsc}} \cdot \left[k_{isc} \cdot \int_0^t e_r(t)dt - Q_G \right] \\
\Delta V_{G1} &= \frac{X_t + X_{eq}}{T_{vsc}} \cdot \frac{\Delta t^2}{2} \cdot (\bar{Q}_G - Q_{G1}) + \\
&\quad \frac{X_t + X_{eq}}{T_{vsc}} \cdot \frac{\Delta t^2}{2} \cdot \Delta Q_{gref} \\
\Delta Q_{G_REF} &= Q_{G_M/m} \cdot k_{isc} \cdot e_r(t) \cdot \frac{\Delta t^3}{2} + \\
&\quad Q_{G_M/m} \cdot k_{psc} \cdot e_r(t) \cdot \Delta t
\end{aligned} \tag{3}$$

$$\begin{aligned}
\frac{\Delta V_G}{\Delta t} &= \frac{X_t + X_{eq}}{T_{vsc}} \cdot Q_{G_M/m} \cdot k_{isc} \cdot e_r(t) \\
\Delta V_G &= \frac{X_t + X_{eq}}{T_{vsc}} \cdot Q_{G_M/m} \cdot k_{isc} \cdot e_r(t) \cdot \Delta t
\end{aligned} \tag{4}$$

Then, the index of the step change of the AVR reference can be computed by Eq. (3) depending on the specified time step (Δt).

Table I shows the initial and tuned parameter set of the VMS. The initial parameter are given by the method in [2]. And, the tuned parameters are computed by using sensitivity analysis in Eqs. (3) and (4). With Both sets, the field test is carried out and the results are described in Section 5.

Table I. Initial and Optimal Parameters of VMS

Values	X_t	X_{eq}	T_{VSC}	K_{psc}	K_{isc}
Initial	0.004	0.006	5	2	0.15
Optimal	0.01	0.008	3.2	2.4	0.05

4. Performance Verification with Real-Time Simulation

The RTDS is a fully digital power system simulator operating in real-time, *i.e.*, it can solve the power system equations fast enough to continuously produce output conditions that realistically represent conditions in the real network. It ensures that the calculations associated with each time step (typically, 50 us) are completed within the designated value. Moreover, the accurate power system component models included in the RTDS facilitate the exact real-time simulation for any physical systems [8], [10]. Therefore, it provides a solid framework for testing and evaluating the performance of controllers under the similar condition to real environment in practice. For this reason, the RTDS is now being used in many universities, research institutes, and industries over 30 countries worldwide [10].

For constructing similar environment to a real power system in the laboratory, the CVC and four RPDs are realized with the RTDS and the parameters can be tested under the similar environment to the real Jeju power system [8].

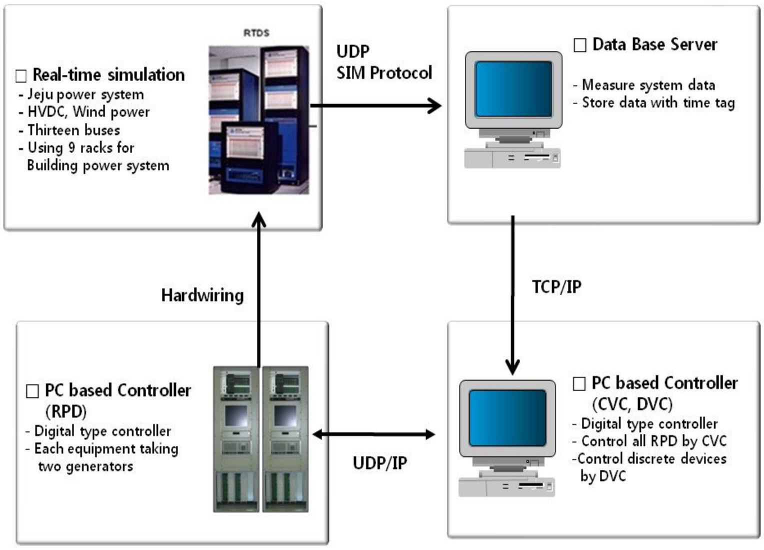

Figure 3. Hardware Set-Up For Real-Time Simulation of the Vms.

Figure 3 shows the hardware set-up for real-time simulation for the VMS. The RTDS simulates the Jeju power system in real-time and RPD and CVC controllers produces control signals by getting system status from the RTDS with hardwiring cable. The Data base server acts like energy management system (EMS) and hence the system status and operating point are computed in this server. With the server, the power flow can be computed and the DVC can compute the reactive power demand of the shunt capacitors in the system and instruction signal can be generated to add or subtract the amount of the connected shunt capacitors.

On the other hand, the second main issue is to confirm the operation performance with the real-time simulation. It is very important step prior to install in physical system. If some problem is found in this step, the system needs to be inspected in detail.

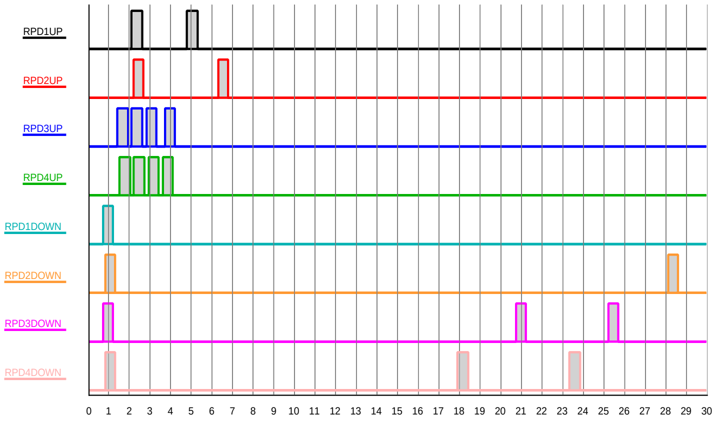

Figure 4. Tap Signals Induced By VMS to Generator.

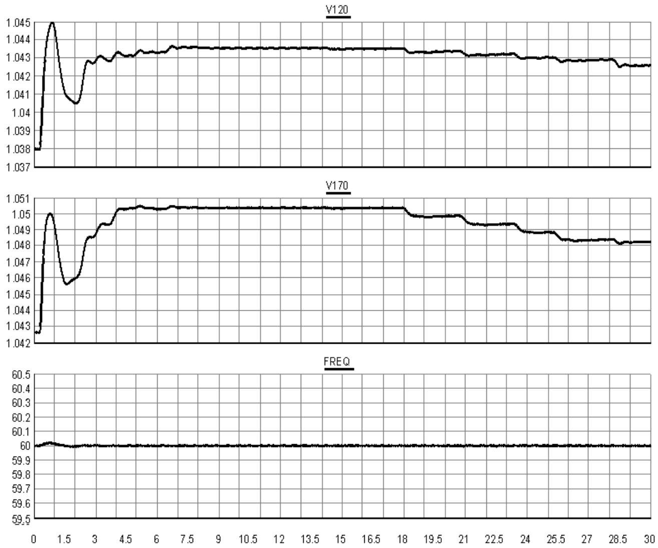

Figure 5. Variations of System Voltages and Frequency.

Figures 4 and 5 show the test results with the real-time test-bed system. When the system load decreases, it is for checking how to operate the VMS in order to maintain system voltage. As shown in the Figure 3, the VMS induces the signal to increase the terminal voltage of the generator in early several seconds. Then, some down signal is induced to balance the reactive power generation. Figure 4 shows the system voltages in main bus in Figure1 and frequency. For preventing from mutual operation between the VMS and AVR, the VMS acts very slowly to decrease system voltage.

Figure 6 and 7 show variations of real power, reactive power, terminal voltage, and excitation voltage of Northern and Southern generators, respectively. As shown in these figures, the generators acts to balance the reactive power and voltage during early several seconds and becomes stable [16].

Figure 6. Variations of Real Power, Reactive Power, Terminal Voltage and Excitation Voltage of Northern Generator.

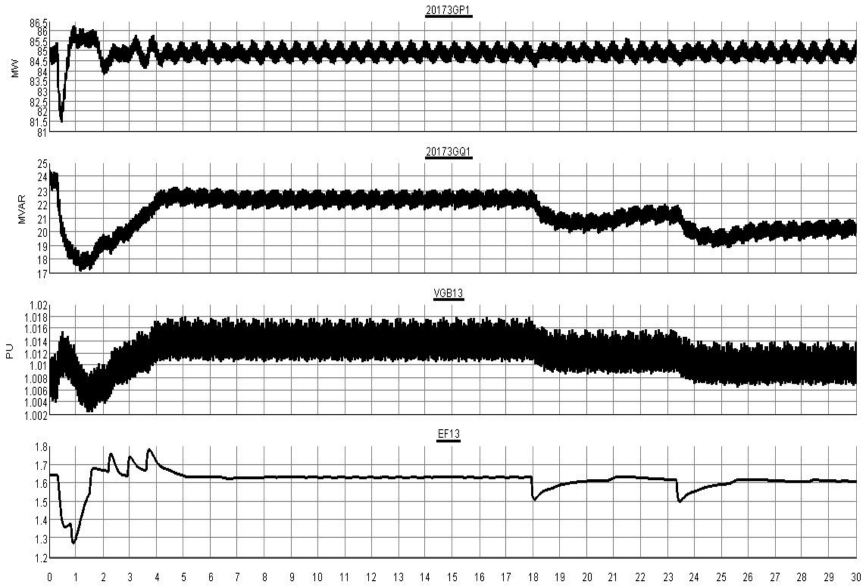

Figure 7. Variations of Real Power, Reactive Power, Terminal Voltage and Excitation Voltage of Southern Generator.

5. Field Application and Results

After examining the performance of the VMS with real-time simulation, the VMS is tested in physical system. The locations of the components of the VMS are illustrated in Figure 1. Whole system are connected with hardwiring and communication cable. After checking that the communication is completely normal, the performance of the VMS is tested. Figure 8 shows the performance to balance the reactive power generations of the involved generators.

At that time, three generators are controlled by the VMS, which are one of Northern generators and two of Southern generators. As shown in the figure, the reactive power generations go to balance and maintain stable status [16].

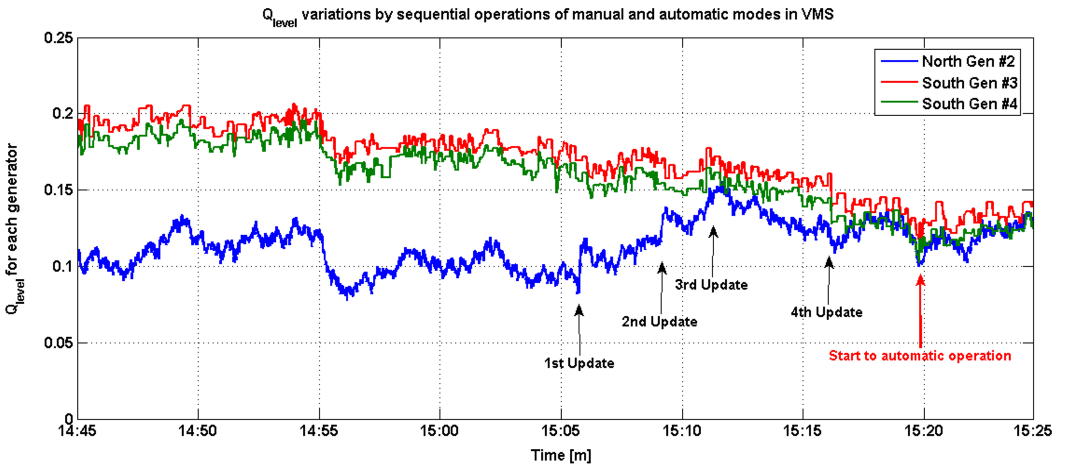

Figure 8. Experiment Result of the Filed Application of the VMS.

6. Conclusions

The paper described implementation and application of voltage management system (VMS) to a physical power system to bring stable and robust operation. The VMS was used to maintain the system voltage within stable range. Especially, the CVC induced a supplementary signal to automatic voltage regulator (AVR) to balance reactive power generation of all involved generators.

In the paper, the physical application of the VMS was described and the important considerations were introduced. One was to tune the parameters of the VMS by sensitivity analysis in field test. The other was to verify the performance by real-time simulation with the real-time digital simulator (RTDS). Finally, the paper showed the results of the stable application of the VMS.

Acknowledgements

This work was supported by the research grant of the Kongju National University in 2015.

References

[1] S. Corsi, P. Marannino, N. Losignore and G. Moreschini, “Coordination Between the Reactive Power Scheduling Function and the Hierarchical Voltage Control of the EHV ENEL System”, IEEE Transactions on Power Systems, vol. 10, no. 2, **(1995)**, pp. 686-694.

[2] S. Corsi, “The Secondary Voltage Regulation in Italy”, IEEE/PES 2000 Summer Meeting, July 16-20, Seattle, Washington, **(2000)**.

[3] S. Corsi, M. Pozzi, C. Sabelli and A. Serrani, “The Coordinated Automatic Voltage Control of the Italian Transmission Grid – Part Ⅰ: Reasons of the Choice and Overview of the Consolidated Hierarchical System”, IEEE Transactions on Power Systems, vol. 19, no. 4, **(2004)**, pp. 1723-1732.

[4] S. Corsi, M. Pozzi, C. Sabelli and A. Serrani, “The Coordinated Automatic Voltage Control of the Italian Transmission Grid – Part Ⅱ: Control Apparatuses and Field Performance of the Consolidated Hierarchical System”, IEEE Transactions on Power Systems, vol. 19, no. 4, **(2004)**, pp. 1733-1741.

[5] J. L. Sancha, J. L. Fernandez, A. Cortes and J. T. Abarca, “Secondary Voltage Control: Analysis, Solution and Simulation Results for the Spanish Transmission System”, IEEE Trans. on Power Systems, vol. 11, no. 2, **(1996)**, pp. 630-638.

[6] J.P. Paul, J.T. Leost and J.M. Tesseron, “Survey of the Secondary Voltage Control in France: Present Realization and Investigations”, IEEE Transactions on Power Systems, vol. PWRS-2, no. 2, **(1987)**, pp. 505-511.

[7] H. F. Wang, H. Hi and H. Chen, “Coordinated secondary voltage control to eliminate voltage violations in power system contingencies”, IEEE trans. on Power Systems, vol.18, no.2, **(2003)**, pp.588-595.
[8] S. -M. Baek, S. C. Nam, J. Y. Song, J. G. Lee, T, K, Kim and J. H. Shin, “Design of Advanced Voltage Management System Including Manual Operation Mode via Real-Time Digital Simulator”, IEEE Trans. Industry Applications, vol.49, no.4, **(2013)**, pp. 1817-1826.
[9] S. Seo, Y. Choi, S. Kang, B. Lee J. Shin and T. Kim, “Hybrid Control System for Managing Voltage and Reactive Power in the JEJU Power System”, Journal of Electrical Engineering & Technology, vol. 4, no.4, **(2009)**, pp.429-438.
[10] Seung-Mook Baek and Jung-Wook Park, “Nonlinear Parameter Optimization of FACTS Controller via Real-Time Digital Simulator”, IEEE Trans. Industry Applications, vol.49, no.5, **(2013)**, pp. 2271-2278.
[11] J. Nocedal and S. J. Wright, Eds., Numerical Optimization. NewYork,NY, USA: Springer-Verlag, **(1999)**.
[12] S.-M. Baek, “Design of PSS and SCRC Controllers to Damp out Low-Frequency Oscillations in Power System”, International Journal of Control and Automation, vol.7, no.10, **(2014)**, pp.283-292.
[13] S.-M. Baek, “Sensitivity Analysis Based Optimization for Linear and Nonlinear Parameters in AVR to Improve Transient Stability in Power System”, International Journal of Control and Automation, vol.8, no.7, **(2015)**, pp.167-174.
[14] J.-F. Chi, Y.-K. Hu and K. Zhao, “An Optimization Method of the Maximum Torque per Ampere for the Self-tuning of the PMSM Robust”, International Journal of Control and Automation, vol.8, no.11, **(2015)**, pp.69-80.
[15] G. V. Lakhekar, “Tuning and Analysis of Sliding Mode Controller Based on Fuzzy Logic”, International Journal of Control and Automation, vol.5, no.3, **(2012)**, pp.93-110.
[16] Korea Electric Power Corporation, Development of a secondary voltage regulator in KEPCO system (Final report), **(2010)**.

Authors

Seung-Mook Baek, he was born in Seoul, Korea. He received B.S., M.S., and Ph.D. degrees from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea, in 2006, 2007, and 2010 respectively, He is currently an Assistant Professor in the Division of Electrical, Electronic and Control Engineering, Kongju National University, Cheonan, Korea. He was a Research Engineer with KEPCO Research Institute, during 2009-2012. His current research interests are in power system dynamics, hybrid systems, optimization control algorithms, real-time simulation, flexible ac transmission system (FACTS) devices, and control of distributed generations.

Hee-Jin Lee, he was born in Ulsan, Korea. He received B.S., and Ph.D. degrees from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea, in 2008 and 2013 respectively. He is currently an Assistant Professor in the Department of Electronic Engineering, Kumoh National Institute of Technology, Gumi, Gyeongbuk, South Korea. He was a Research Engineer with Hyundai Heavy Industries, during 2013-2015. His current research interests are in system integration, power system protection, power system dynamics, and flexible ac transmission system (FACTS) devices.