Field Implementation of Voltage Management System (VMS) into Jeju Power System in Korea

Jeonghoon Shin†, Suchul Nam*, Jiyoung Song*, Jaegul Lee*, Sangwook Han*, Baekkyung Ko†, Yongho An*, Taekyun Kim*, Byungjun Lee** and Seungmook Baek***

Abstract – This paper presents the results of field tests on Voltage Management System (VMS) using hybrid voltage control, which utilizes coordinated controls of various reactive power resources such as generators, FACTS and switched shunt devices to regulate the pilot bus voltage in a voltage control area. It also includes the results of performance test on RTDS-based test bed in order to validate the VMS before installing it in Jeju power system. The main purpose of the system is adequately to regulate the reactive power reserve of key generators in a normal condition with coordination of discrete shunt devices such as condensers and reactors so that the reserves can avoid voltage collapse in emergency state in Jeju system. Field tests in the automatic mode of VMS operation are included in steady-states and transient states. Finally, by the successful operation of VMS in Jeju power system, the VMS is proved to effectively control system voltage profiles in steady-state condition, increase system MVAR reserves and improve system reliability for pre- and post-contingency.

Keywords: Voltage Management System (VMS), Reactive power reserve, Coordinated voltage control, Real Time Digital Simulator (RTDS)

1. Introduction

Voltage control to mitigate voltage instability of modern power system is one of main concerns to power system operators. Due to their complexity and load characteristics in recent power systems, maintaining desired voltage profiles has been very difficult. Especially for Korean power system, about 42% of system loads are concentrated on the Seoul metropolitan area; however, key generators are located at the southern coastal area. Therefore, most of electric powers are flowing into the Seoul metropolitan area through six transmission lines which include two 765kV lines and four 345kV lines. When one of 765kV lines is tripped, the whole system will be collapsed because of system voltage instability. It is the reason why we have special protection schemes (SPS) in the system to make system stable for emergent contingencies through shedding the loads up to 1,500MW of the loads in Seoul area. Under current situation, the system operator of Korea has been interested in hierarchical voltage control, which was initially proposed in several European countries. They have firstly proposed a secondary voltage control which can control the voltages of generators through controlling reactive powers to maintain the pilot bus voltage in a voltage control area [1-9]. The desired voltages on the pilot buses come from the results of optimal voltage-var planning in the energy management system of independent system operators. Like frequency controls by Automatic Generation Control (AGC), system operators want to control the pilot bus voltages automatically by controlling the reactive powers of the participated generators which can be representative ones in a voltage control area.

In South Korea, a hybrid voltage control system called Voltage Management System (VMS) based on hierarchical voltage control has been developed since 2009 and installed at Jeju Island. Hybrid control means the coordinated control of Continuous Voltage Controller (CVC) such as generators, FACTS, synchronous condensers and Discrete Voltage Controller (DVC), which includes transformer tap changers, switched shunt capacitors and reactors. The detail descriptions related to the development of VMS are given in [12-14].

This paper presents the field test results of VMS in order to validate the performance of the developed system and includes the simulation results on RTDS-based test-bed of Jeju Island. Jeju Island was finally selected as the voltage control area for implementing VMS to real power system. Four generators are participated under VMS control and the switched shunt capacitors on nine 154kV buses as well (Fig. 1). Totally, four steps have been made for the final implementation of VMS to real power systems. The first two steps include RTDS simulations and the field test for the early-developed version of VMS and the second for the final updated version of VMS which was
revise the CVC algorithm more efficiently from manual initialization method to automatic one. Also, hardware model of Reactive Power Dispatcher (RPD) was changed to on-board chip set from modular rack-type board.

This paper consists of four parts. Section II gives brief description of VMS finally applied to Jeju power system. Section III presents the results of RTDS simulations. In addition, the results for field implementation are given in Section IV after revision of the requirements derived from the first field implementation of VMS. Conclusions with insights and future expansion plans of VMS are given in section V.

2. Voltage Management System of KEPCO

2.1 Block diagram of VMS

This section introduces the overall VMS structure which was finally installed at Jeju power system. The CVC algorithm in VMS was originally developed to have manual operation mode for the mitigation of initial transient problem. Finally, it is changed to have automatic mode without transient problem after the first field implementation in Jeju power system. Fig. 2 indicates the block diagram of Advanced Voltage Management System (AVMS), which was already introduced in the paper [12]. However, the final block diagram of VMS installed at Jeju power system is without manual mode parts in Fig. 2.

Because if the RPD mode is selected by AVR operators instead of AVR mode, the amount of differences resulted from the different operating points will be automatically applied to change AVR references step by step so that all generators reach to the same reactive power level. Then, the injection or rejection of VMS into the living condition of generators no longer makes any transient problem. In RTDS simulation, this effect can be simulated by changing the way for RPD to give signals to AVR (of generators in RTDS) from discretely (digital) to continuously (analog). The results will be shown in Section III.

In North America, some utilities want to control AVR directly by using EMS signals without RPD actions. They call it AVC (Automatic Voltage Control).

2.2 CVC (Continuous Voltage Controller) algorithm

The VMS installed at Jeju power system is based on hierarchical voltage control as mentioned in the previous section. For the tertiary level control, optimized values of the pilot bus voltages are calculated by solving various optimization problems such as power loss minimization, maximizing stability margin. In this study, the desired voltage on the pilot bus was determined to 160kV according to the optimization result for power loss minimization in the system. The control strategy in the CVC, which basically follows the European SVC, consists of two parts, as shown in Fig. 5. A proportional-integral part is the first part as given below.

\[
E_p(t) = V_p^{ref}(t) - V_p(t)
\]

\[
Q_g \% = k_{pi} \cdot E_p(t) + k_{ic} \cdot \int E_p(t) dt
\]

where \(V_p(t)\) represents the voltage of pilot bus at time \(t\), \(V_p^{ref}(t)\) is the voltage reference at time \(t\) derived from tertiary level control, \(Q_g \%\) is the reactive power to be generated in each RPD, \(k_{pi}\) and \(k_{ic}\) are the proportional and integral gains in the CVC, respectively. In the scheme, the reactive power levels have to be generated in each RPD and sent back to the RPD controllers. The second part is the integral structure for RPD as follows.

\[
E_p(t) = Q_g^{ref}(t) - Q_g(t)
\]

\[
Q_g^{ref}(t) = Q_g \% \cdot Q_g^{M/n}
\]

\[
\Delta V_p(t) = k_{ic} \cdot \int E_p(t) dt
\]

where \(Q_g(t)\) indicates the reactive power of each generator at time \(t\), \(Q_g^{ref}(t)\) is the reference of reactive power at time \(t\) derived from (1), \(Q_g^{M/n}\) represents the reactive power limits of each generator and \(k_{ic}\) is the
Field Implementation of Voltage Management System (VMS) into Jeju Power System in Korea

integral gain of RPD in Fig. 5. The purpose of RPD in VMS is to control the reactive powers of each generator through sending the signal to the AVR to change the reference terminal voltage. The amount of reactive power to be generated in each generator is determined by using the reactive power output by each generator can equally be maintained at the same level by the CVC. It is very good characteristic of VMS because, normally, voltage instability used to be started when the reactive power produced in a single generator within a voltage control area reaches to its maximum value. Therefore, equally balancing the reactive powers of generator’s reactive powers in the area makes the voltage collapse be delayed to some time. In case of emergency, it is very beneficial for system operators to handle the situation properly.

2.3 DVC (Discrete Voltage Controller) algorithm

Another feature of the VMS developed by KEPCO is to have the function of coordinated control between CVC and DVC in order to maintain the required reactive power reserves of generators within a voltage control area. To maintain the reactive power reserves in an area, generators should have proper reserves for the severe contingencies. In order to do so, after finishing the CVC operation to meet the desired voltages on pilot buses and if the desired reactive power reserves are not achieved, the DVC of the VMS will be operated. The DVC algorithm selects the discrete control devices. The formulation of the algorithm is written as follows:

\[
\text{Minimize} \sum_{j=1}^{n} \left[ s_j \cdot C_{\text{swt}} + \sum_{j=1}^{n} w_{i,j} \cdot P_j(Q_{i,j}) + \sum_{k=1}^{n} P_k(V_{i,k}) \right]
\]

\[\text{s.t.: } \sum_{i=1}^{N} s_i \leq N_{\text{swt}}, \quad s_i \in [-1, 0, +1] \]

3. Simulation results on test-bed

3.1 Configuration of RTDS-based test-bed

Fig. 4 (a) shows the configuration of RTDS-based test-bed constructed in KEPCO research institute, Korea for the test of external devices such as newly developed control devices and digital protective relays and so on. Many control devices and digital protective relays have been validated on the test-bed before installation in real power system since it was developed in 2005. The RTDS setup on test-bed for real-time simulation to validate the function of VMS is represented in Fig. 4 (b). Jeju power system model was constructed by using real data of Jeju Island on July, 2010. Fig. 1 shows the one line diagram of Jeju power system. The maximum power demand was about 550MW, and a HVDC lines fed 150MW to the Jeju Island. The HVDC system in RTDS is modeled to operate as constant power mode. 9 racks are used for the simulation. Hard-wired connections for the interface between RTDS and RPD to send the control signal to AVRs of the generators modeled in RTDS are used.

3.2 Simulation results for the validation of VMS

As presented in [12], the AVMS algorithm to avoid transient phenomena on VMS injection or rejection was successfully operated in the simulation. However, the final
VMS algorithm installed in Jeju, which is eliminated the manual mode part of Fig. 2, has the better performance than manual mode in the simulation. The gap of initial reactive power outputs between two generators in Northern area are automatically converged by one step as shown in Fig. 5(c). Unlike the manual mode operation, pre-calculated indices needed for the references of AVRIs to be changed are applied at one time in the automatic operation mode. Then, according to the dynamic operating conditions, the reactive power outputs of two generators are getting closer to a balanced point. For comparison, all three results are represented in Fig. 5.

In order to test the performance of VMS to be installed in Jeju power system on test-bed, several cases have been prepared. First of all, because the VMS should obey the desired pilot bus voltage (Bus 120 in Fig. 1), which comes from the result of tertiary control, the case for intentional change of the reference voltage on the bus are simulated. Next, the case for small variation of loads in Jeju power system is investigated. In particular, this case is important because one of main purposes of VMS installation should be improvement of voltage quality in the area. Another one is for the coordinated control with discrete voltage controllers including switched shunt capacitors located in 154kV substations in Jeju power system. Total amount of installed capacitors in the system is up to 120MVar. Lastly, compared to the above mentioned cases, the worst contingency case is prepared to check the effect of VMS operation. Generally, VMS should be blocked if large contingencies such as line tripping, loss of generators, severe faults on the buses near the controlled buses are occurred. However, this generator tripping case is intentionally prepared for checking how the VMS can contribute to this kind of system condition. The cases are summarized in Table 1.

Table 1. Case summary for simulation

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Purpose of the case</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Raise up the desired voltage of the pilot bus</td>
<td>Validate the proper operation of VMS to follow the desired voltages of the pilot bus</td>
</tr>
<tr>
<td>II</td>
<td>Change the loads of the bus to some amount</td>
<td>Check the balance of reactive powers of controlled generators</td>
</tr>
<tr>
<td>III</td>
<td>Switch on the capacitors of the bus</td>
<td>Check the effect of VMS operation</td>
</tr>
<tr>
<td>IV</td>
<td>Generator trip (large disturbance)</td>
<td></td>
</tr>
</tbody>
</table>

(a) Without AVMS

(b) With manual mode of AVMS

(c) With automatic mode of AVMS

Fig. 5. Reactive powers of generators in the northern area

(a) Pilot bus voltage (Bus 120, 1.041pu → 1.045pu)

(b) Reactive powers of the generators controlled by VMS

Fig. 6. Simulation results for Case I
3.2.1. Case I: Change the voltage set-point of the pilot bus

As shown in Fig. 6 (a), the desired voltage of the pilot bus was successfully controlled by RPD operations of VMS at 210 msec. Also, the outputs of two sets of controlled generators were finally balanced, respectively, due to the VMS as represented in Fig. 6 (b). The generators in the South (G#3, G#4) produced 12 MVar more than before to raise the pilot bus voltage and 8MVar for the North (G#1, G#2). About 20MVars from four generators were contributed to raise the pilot bus voltage to 1.045pu.

3.2.2. Case II: Increase the loads on Bus 160

In order to check the ability of VMS to control the voltage of pilot bus and sensitivity of voltage due to the load variation on a bus in the system, around 40MW of bus load was increased in the case.

As a result, the pilot bus voltage was decreased to below 1.03 pu during 70 seconds. After then, the voltage was gradually recovered to the initial value by the successful operation of VMS as represented in Fig. 7 (a). On the other hand, both of RPDs determine the amount of reactive powers of generators by changing the references of AVR, according to the value of $Qg_s$, which are calculated from CVC.

3.2.3. Case III: Switch on the capacitors on Bus 200

Through the simulation of this case, we can easily expect how VMS can maintain reactive power reserves of generators in a voltage control area by coordinated control of CVC and DVC. As shown in Fig. 8 (b), exactly the same amount of reactive powers of 10MVar as shunt capacitors are switched on was decreased from all generators controlled by VMS. The generators in the North (G#1, G#2) reduced their outputs as 0.5MVar and 2.5MVar, respectively. The Southern generators (G#3, G#4), whose electric distances might be closer than the Northern ones, also reduced their reactive power outputs as 3MVar and 4MVar, respectively. Electrically, the location of G#1 seems to be far away from the bus 200, which has the capacitor bank switched on (Fig. 1). Because of the reason, the variation of reactive power output of G#1 in the Fig. 8 (b) is very small compared to other generations. Consequently, the voltage of pilot bus was recovered to the desired point and at the same time the reactive power reserves of generators are increased due to the proper operation of VMS.

3.2.4. Case IV: Trip one of controlled generators

In the middle of VMS operation, sudden blocking of a major generator was occurred in the simulation. Due to the loss of generation (55MW+ j24MVar), the pilot bus voltage was significantly dropped at the moment. Then, fortunately in the case, the voltage was controlled by VMS so that it could be recovered to some extent but not to the desired voltage (Fig. 9 (a)). The reason should be the lack of
reactive powers in the area. As represented in Fig. 9 (b), only two generators (G#1, G#2) controlled by VMS with small capacity and one uncontrolled generator (G#4) were remained in the system. G#4 has been automatically tripped out of VMS control when G#3 was blocked at the beginning. Therefore, there were not enough reactive powers remained in the system to cover the loss of 24 MVar.

4. Field Applications

After successful performance tests on RTDS-based test-bed, several experimental tests at Jeju power system were carried out in April of 2012, September and October of 2013, respectively. Like the tests on RTDS-based test-bed, the results of three test cases are finally summarized in this section. Table 2 shows the case summary.

Table 2. Case summary for field tests

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Purpose of the case</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Change the target voltage of the pilot bus</td>
<td>Validate the proper operation of VMS to follow the desired voltages of the pilot bus</td>
</tr>
<tr>
<td>II</td>
<td>Light-loaded condition at night on 24-hour test (load decrease)</td>
<td>Check the balance of reactive powers of controlled generators</td>
</tr>
<tr>
<td>III</td>
<td>Switch on the capacitors on 24-hour test</td>
<td></td>
</tr>
</tbody>
</table>

4.1 Case I: Change the voltage set-point of the pilot bus

In the case, the voltage set point of the pilot bus was changed up and down intentionally to check a basic control function of VMS installed in real power system.

As shown in Fig. 10 (a), the voltage was controlled successfully by the operation of VMS. The RPDs of VMS changed the references of four AVR devices so that reactive power outputs of generators controlled by VMS were raised and lowered consecutively.

4.2 Case II: Light-loaded condition (load decrease)

During 24-hour test of VMS in Jeju power system, system loads were significantly decreased due to the light-loaded condition at night.

Because of this load decreased condition, the set point of the desired pilot bus voltage was intentionally changed from 1.044 pu to 1.042 pu as shown in Fig. 14 (a). In addition, G#2 in Northern area stopped its generation according to the daily generation schedule approximately at 22:00. Therefore, the pilot bus voltage could be maintained within the desired value due to proper control of the reactive power outputs of generators by VMS as presented in Fig. 14 (b), even though the system load was continuously decreasing.
4.3 Case III: Switch On the capacitor bank on Bus 220

During the same test as in the previous case, 20MVar of the capacitor bank on a bus was switched on. Then, the pilot bus voltage was slightly increased as shown in Fig. 15. (a). As represented in Fig. 15 (b), through the operation of VMS, the reactive powers of four generators were gradually lowered so that the voltage on the pilot bus was finally decreased to the desired voltage. Therefore, in terms of reactive power reserves of generators, it could be considered as more reserves are kept in the system. If the severe contingencies related to the voltage instability are occurred, at that time, generators could produce more reactive powers into the system. It could be one of benefits of the system with existence of VMS.

Related to the test on the coordinated control of VMS, the results are shown in Fig. 13. After all of the CVC operations are finished to meet the desired voltage of pilot bus, the DVC algorithm is then executed to keep the system reserve of reactive powers to the target value (0.9 in this case). When the system reserve does not meet the desired value or the specified range, the DVC algorithm calculates the optimal location and the amount of reactive powers to be compensated by discrete reactive power compensator such as shunt reactors and capacitors.

Fig. 13(a) shows the variation of pilot bus voltage according to the DVC operations. After triggering the DVC operations at the beginning, in this case, 5 MVar of the capacitor bank on a bus was needed to be out of service to meet the desired system reserve (Because there are no shunt reactors to reduce the voltage of the bus installed in Jeju power system, capacitors are the only control option to handle it). It seems that too much reserve was kept in the system compared to the desired value. All of three capacitor banks were out of service in the test. Suppose the VMS is not installed in the system on the same case, the pilot bus voltage will not be recovered to the desired voltage without meeting the system reserve.

Fig. 13 (b) and (c) shows the variation of reactive powers of generators and the reserve rate of the system. The effect of VMS operations would be simply expected by these figures. Unlike the simulation on the test-bed, the speed of voltage change due to the control of reactive powers was quite slow. It can be evaluated that system inertia and interaction between reactive power controllers would be main reasons.

5. Conclusion

The voltage management including voltage quality and instability is currently a critical issue in Korean power system. Because of generation-load imbalance
characteristics, especially for Seoul metropolitan area, voltage instability can be occurred to lead the whole power system collapsed when critical contingencies are occurred in the system. Additionally, rigid voltage criteria, which should be maintained as a reliability regulation in Korea, would be another burden to system operators. In order to overcome these issues, KEPCO developed a hybrid voltage control system called VMS, which controls the pilot bus

Fig. 13. Field test results for Case III
Field Implementation of Voltage Management System (VMS) into Jeju Power System in Korea

voltage by using CVC and DVC coordinately. Through the successful simulation test on RTDS-based test-bed, as previously mentioned above section in the paper, several field implementation tests were successfully performed at Jeju power system. Based on these results of the field application, the performance of VMS was finally verified.

Consequently, we can see that VMS can improve the voltage quality of the given power system through controlling reactive power resources and enhance the voltage stability by balancing the reactive power outputs of generators. Also, VMS would provide the operators the longer time to do control actions for severe events in the system by delaying the time of voltage collapse. The validated VMS, in the near future, will be expanded to be installed at the main land of Korea.

Of course, all the benefits including the improvement of voltage quality, enhancement of system stability will be the same in the main land.

References


Jeonghoon Shin He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from KyungPook National University, Korea, in 1993, 1995 and 2006, respectively. He was a Visiting Scholar at EPRI (Electric Power Research Institute), Palo Alto, CA, USA, from March 2003 to Feb. 2004. He has been with KEPRI, the research institute of Korea Electric Power Company (KEPCO), as a Principal Research Engineer since 1995. His research interests include real-time digital simulation, transient and dynamic stability, and power system planning and operation.

Suchul Nam He received his B.S. and M.S. degrees in Electrical Engineering from Korea University, Korea, in 2001 and 2006, respectively. Mr. Nam joined KEPRI’s Power System Lab. as a research engineer in Feb. 2006, where he is now developing an integrated optimization scheme for a reactive power management system for KEPCO. He is also participating in several transmission power system studies.
Jeonghoon Shin, Suchul Nam, Jiyoung Song, Jaegul Lee, Sangwook Han, Baekkyung Ko, Yongho An, Taekyun Kim, Byungjun Lee and Seungmook Baek

Jiyoung Song He received his B.S. degrees in Electrical and Electronic Engineering from Hanyang University in 2008, and M.S. degrees in Electrical Engineering from Korea University in 2010. Mr. Song joined the Korea Electric Power Company (KEPCO) Research Institute (KEPRI) as a research engineer in 2010. His research interests include power system analysis, device modeling, planning and operation, real-time digital simulation.

Jaegul Lee He received his B.S. and M.S. degrees in Electrical Engineering from Incheon University in 2001 and 2003, respectively. Upon graduating from Incheon University, Mr. Lee joined the Korea Electric Power Company (KEPCO) Research Institute in 2004. In KEPRI, he was involved in several project areas, including real-time simulation of transient phenomena, model development, and studies involving power electronics.

Sangwook Han He received B.S., M.S. and Ph.D degrees in Electrical Engineering from Korea University, Korea in 2004, 2006 and 2012 respectively. He is currently a senior researcher in KEPRI which is research institute of KEPCO. He is interested in the stabilities of the power system and the synchro-phasor applications

Baekkyeong Ko He received his B.S. degrees in Electrical Engineering from Hoseo University, Korea, in 2011 and M.S. degrees in Electrical Engineering from Korea University, Korea, in 2013. Mr. Ko joined KEPRI’s Power Transmission Lab. as a researcher in Sep. 2013, where he is now researching dynamic HVDC models for KEPCO power system. He is also studying for reducing fault current in capital area, Korea from a power system planning perspective

Yongho An He received his B.S degree in Electrical Engineering from Incheon University, Korea, in 1984 and M.S. Ph.D from Cheonbuk University, in 2000 and 2013, respectively. He has been with KEPRI, the research institute of Korea Electric Power Company (KEPCO), as a Principal Research Engineer since 1987. His research interests include IEC 61850 based digital substation engineering.

Taekyun Kim He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Hanyang University, Korea, in 1986, 1989 and 1993, respectively. He is a principal research engineer in KEPRI, Korea. He has been a project leader in several simulator studies related to the development of various models and software for the KEPS. His research interests include real-time digital simulation, transient and dynamic stability, as well as power system planning and operation.

Byongjun Lee He received B.S. degree from Korea University, Seoul, Korea in 1987, M.S. and Ph.D degrees in Electrical Engineering from Iowa State University in 1991 and 1994 respectively. He is currently a professor in the School of Electrical Engineering at Korea University

Seungmook Baek He received the B.S., M.S., and Ph.D. degrees from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, in 2006, 2007, and 2010, respectively. He is currently an Assistant Professor with the Division of Electrical, Electronic and Control Engineering, Kongju National University, Cheonnam, Korea.