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Design of a Cooperative Voltage Control System Between EMS (VMS) and DMS

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Abstract

This paper presents the conceptual design of a cooperative control with Energy Management System (EMS) and Distribution Management System (DMS). This control enables insufficient reactive power reserve in a power transmission system to be supplemented by surplus reactive power in a power distribution system on the basis of the amount of the needed reactive power reserve calculated by the EMS. This can be achieved, because increased numbers of microgrids with distributed energy resources will be installed in the distribution system. Furthermore, the DMS with smart control strategy by using surplus reactive power in the distribution system of the area has been gradually installed in the system as well. Therefore, a kind of hierarchical voltage control and cooperative control scheme could be considered for the effective use of energy resources. A quantitative index to evaluate the current reactive power reserve of the transmission system is also required. In the paper, the algorithm for the whole cooperative control system, including Area-Q Indicator (AQI) as the index for the current reactive power reserve of a voltage control area, is devised and presented. Finally, the performance of the proposed system is proven by several simulation studies.

Keywords: *Hierarchical Voltage Control, Voltage Management System, Distribution Management System, AQI*

I. Introduction

A voltage problem in a power system, unlike frequency, is regarded as a local phenomenon. Accordingly, in order to maintain the voltages of substations within a predetermined range, individual voltage compensators (e.g., a capacitor, a reactor, Flexible AC transmission system (FACTS), etc.) are installed and operated at each substation. An operating scheme using such a voltage compensator is effective from the standpoint of the maintenance of voltage for each substation, but at present is inefficiently operated, because the scheme does not take into consideration reactive power sources installed near the substation to maintain the voltage quality of the entire system. Furthermore, with the rapid development of Information Technology (IT) and high-speed computing capability, technologies for managing the voltage quality of the entire system via a Voltage Management System (hereinafter referred to as "VMS") have recently been developed. For example, the VMS divides the entire power system into a plurality of electrically isolated voltage control areas, so as to manage voltage quality using voltage control. The VMS selects a representative substation of each voltage control area. The VMS cooperatively controls reactive power sources (e.g., power generators, capacitors, reactors, and FACTS) installed in local systems, so that the voltage of the selected representative substation (pilot bus) is maintained at a uniform level (e.g., 1.0 p.u.).

Such a VMS is configured to control the voltage of a power transmission substation (of 154 kV or more), and is operated in such a way that it is mounted on a central energy management system (hereinafter referred to as "EMS"), or configured as a separate device. The EMS processes a 22.9 kV or less power distribution system as a load, and performs energy management via Automatic Tap Changer (Automatic Voltage Regulator, AVR) of a transformer, without including the power distribution system in an operation target. Here, an AVR is operated separately from the EMS, and is configured to maintain a secondary side voltage of a 154 kV/22.9 kV transformer within a predetermined range.

In recent power distribution systems, microgrids (MGs) with various distributed power sources have become more popular, and loop operations have been made possible. Accordingly, a Distribution Management System (hereinafter referred to as "DMS") that will manage a complicated power distribution system, as in the case of the EMS of a power transmission system, has been developed.

Fig. 1(a) shows that a current power grid is connected to plenty of loads and power generators. Additionally, distributed power sources, such as wind power, photovoltaic, tidal energy storage devices, and fuel cells, have been gradually increased to install at the secondary side of transformers. However, from the system operator's point of view, they are operated individually without any centralized control, such as EMS or VMS.

Meanwhile, Fig. 1(b) shows that in the future power grid, EMS (or VMS) and DMS will be installed and operated for the overall operation of a power system, including the maintenance of voltage quality of the power grid. That is, the EMS or VMS is connected to a power transmission system to maintain the voltage quality of the power transmission system, while the DMS is connected to a power distribution system to maintain the voltage quality of the power distribution system.

Article Information

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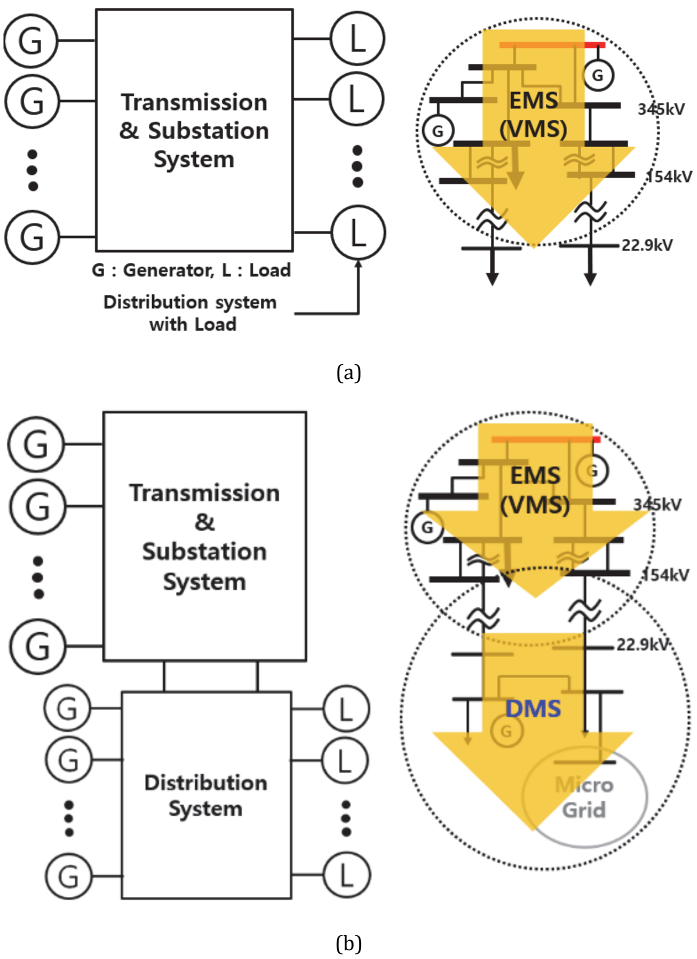

(a)

(b)

Fig. 1. Power grid structures and their voltage control areas. (a) Current power grid and its voltage control area by EMS (VMS). (b) Future power grid and its voltage control area by EMS and DMS.

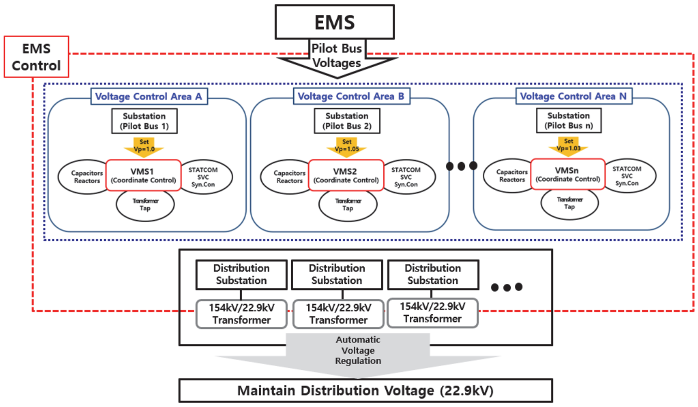

Fig. 2. Voltage control strategy by EMS (VMS).

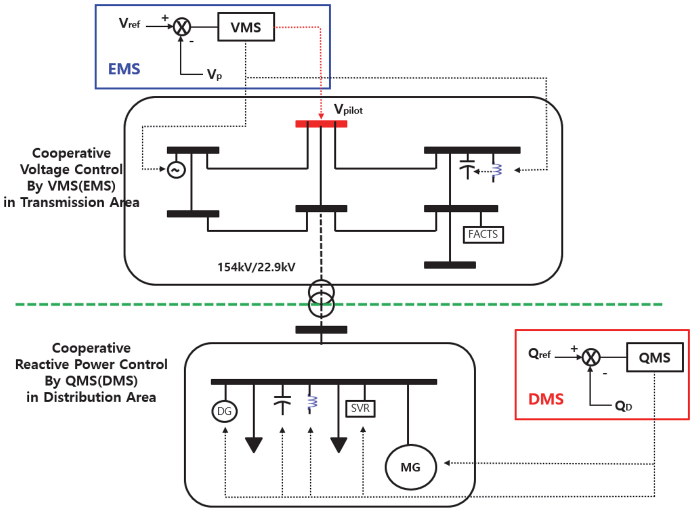

Fig. 3. Voltage and reactive power control by EMS and DMS

Fig. 2 shows that in the power transmission system, the EMS maintains the voltage quality of the power transmission system by performing voltage control based on respective voltage compensators installed in power transmission substations. Of course, a voltage control scheme using the VMS may also be used instead of the voltage control scheme in EMS. Voltage control in the power transmission system using an EMS (or VMS), or voltage control in the power distribution system using a DMS, is independently performed. However, the power transmission system and the power distribution system are connected to each other via a 154 kV/22.9 kV transformer, and thus if necessary, the power transmission system can utilize sufficient energy resources connected to the power distribution system. The voltage of the power transmission system is suitably controlled by means of the EMS (or VMS) for the purpose of maximally securing a dynamic reactive power reserve within the system in the case of a contingency, so as to prevent a wide area power failure from occurring due to voltage instability.

In particular, when a power system is in a normal state without causing accidents (that is, a sufficient reactive power reserve is present in the system), it may be considered that the role of EMS or DMS is desirably performed merely by maintaining its individual function, without mutual cooperative control. In contrast, in the case of a contingency causing voltage instability (that is, when a reactive power reserve is inefficient), there is a problem, in that it is not possible to compensate for reactive power by efficiently utilizing the resources of the system via cooperative control of the EMS and the DMS. Meanwhile, the DMS connected to the power distribution system takes charge of complicated operation of the power distribution system, including the voltage control thereof. That is, the DMS cooperatively controls various distributed power sources and various voltage compensators connected to the power distribution system, thus maintaining the voltage of the power distribution system within the range of predetermined voltages (Fig. 3).

Recently, as the number of various distributed power sources and reactive power compensators connected to the power distribution system has increased, a cooperative control system for efficiently utilizing added resources (e.g., distributed power sources and reactive power compensators) is required. For example, [1] discloses technology for performing cooperative control of reactive power sources using a variation in reactive power. [2] discloses technology for performing cooperative control of reactive power sources using reactive power margin of the reactive power sources. However, the references were focused on the only control devices in an area, not focused on the whole areas we are interested in.

Therefore, in the paper, the cooperative control of EMS and DMS as a method of the whole power system is proposed. Section II describes the VMS as the prior research and development we needed to know for better understanding of the proposed system. Section III proposes the conceptual design of the system, operational principles and functions. In the section, the new index for measurement of current reserves of reactive power in an area is included. Section IV describes the simulation results for verification of the proposed concept. Section V has concluding remarks and future works for real field implementation.

II. Voltage Management System (VMS)

The cooperative control concept proposed in the paper is based on VMS, which was installed at the Jeju island of Korean power system in 2010. Therefore, in order to understand the proposed concept more easily, brief description of the VMS was introduced in the section.

The VMS, as a kind of hierarchical voltage control system which was firstly introduced in several European countries [3]-[9], was developed not only to enhance the voltage quality in the steady-state condition of the system, but also to prevent voltage collapse in the case of critical contingencies. Both objectives of the VMS can be achieved through maintaining enough reactive power reserves of the system by making use of all the reactive power resources participated in the area of the system.

Basically, before applying VMS, a whole system should be divided into several voltage control areas considering electrical distances among reactive power resources and buses. Additionally, one or two pilot buses are selected in an area by calculating the sensitivity of voltage. The reactive power resources are largely classified into two categories in terms of control continuity, the first one is Continuous Voltage Controller (CVC) such as generators, FACTS, synchronous condensers, and the other is Discrete Voltage Controller (DVC), which includes transformer tap changers, switched shunt capacitors and reactors. The VMS installed in Korea controls these two controllers successively so that reactive power reserves in an area can be maintained at all times. [10] and [11] provide detailed descriptions regarding to the development of VMS.

A. CVC control Algorithm and Reactive Power Dispatcher (RPD)

As shown in Fig. 4, the CVC in the upper part has a proportional-integral block, as given below:

$$E_r(t) = V_p^{ref}(t) - V_P(t)$$

$$Q_g\%(t) = k_{psc} \cdot E_r(t) + k_{isc} \cdot \int_0^t E_r(t)dt$$

In the scheme, k_{isc} and k_{isc} are very important two gains in the CVC, those values are changed according to the characteristic of an area. The voltage reference at time t, $V_p^{ref}(t)$ is the result of an optimization from EMS as tertiary level control. The output of CVC, $Q_g\%(t)$, is the percentage of reactive power to be generated in an RPD. By using $Q_g\%(t)$, the amount of reactive power generation can be set in the individual generator.

The RPD represented in the lower part of Fig. 4 has an integral block, as follows:

$$E_q(t) = Q_g^{ref}(t) - Q_g(t)$$

$$Q_g^{ref}(t) = Q_g\%(t) \cdot Q_{g\_M/m}$$

$$\Delta V_g(t) = k_{ir} \cdot \int_0^t E_q(t)dt$$

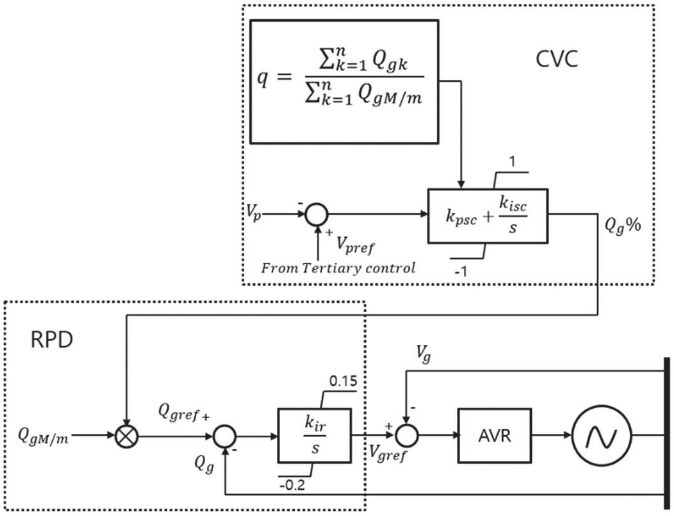

Fig. 4. Block Diagram of VMS developed by KEPCO.

The objectives of RPD is to control the reactive power of the generator by sending a signal to the AVR to move the reference voltage of generator. The RPD is able to control the other continuous voltage compensator such as SVC, STATCOM in the same control way. In Fig. 4, k_{ir} is the integral gain of RPD and $Q_g(t)$ represents a generator reactive power at time t. $Q_{g\_M/m}$ indicates the limitation of reactive power. $Q_g^{ref}(t)$ can be finally determined by multiplying $Q_g\%(t)$ and $Q_{g\_M/m}$, which is the reference value of reactive power at time t.

B. DVC Control Algorithm

The VMS has the function of coordinated control between CVC and DVC. For maintaining voltage quality in normal state and having fast recovery of voltage in the case of emergency, the best way to do is to have a required reactive power reserves of generators and/or dynamic voltage compensator such as SVC and STATCOM as much as possible. Therefore, in order to get the maximum dynamic reserves of reactive power within a voltage control area, all the discrete voltage controllers can be used. After finishing the control operation of CVC and RPD in VMS, if the desired reactive power reserves are not sufficient, the DVC control algorithm will be activated to select the discrete control devices according to the formulation introduced in [11], which gives a detailed explanation of the DVC algorithm.

III. A Cooperative Control System Between EMS and DMS

The proposed system has been made keeping in mind the mentioned problems, and an objective of the system is to provide a method for the cooperative control of an EMS and a DMS, which allow a power transmission system with deficit reactive power reserves to be supplied from the reactive power sources of the power distribution system. This is based on a reactive power reserve detected by the power transmission system, and a required reactive power reserve calculated by the EMS.

A. The Basic Structure of the Proposed System

Fig. 5 shows that in order to accomplish the given objective, the

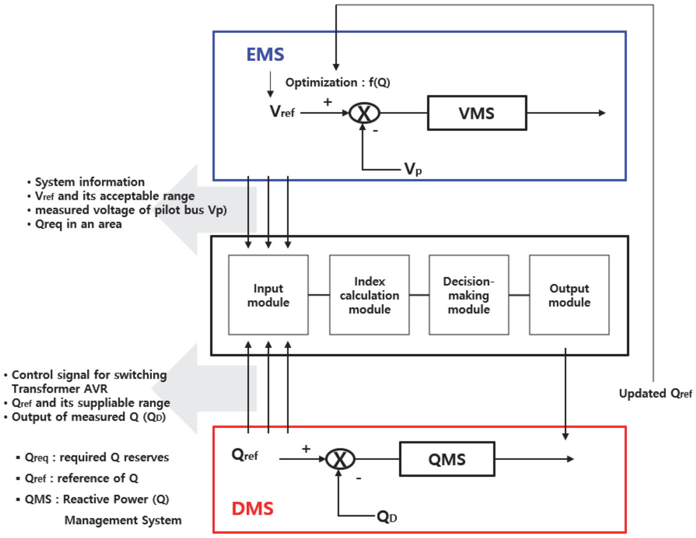

Fig. 5. Input-output structure of the proposed system.

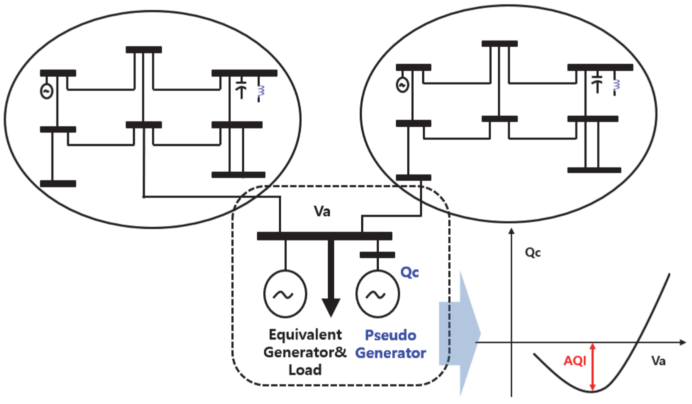

Fig. 6. Conceptual diagram of AQI (Area-Q Index).

system for cooperative control of an EMS and DMS includes an input module for receiving EMS information from the EMS, and DMS information from a DMS. The input module also includes system setting values by the user, such as Qreq (amount of reactive power requirement in the area), Qref (reference value of QMS, as shown in Fig. 3), and the minimum and maximum range of Vref and Qref.

The proposed system also has an index calculation module for calculating an Area Q (reactive power) Index (AQI) based on target system information and power flow data from the EMS. The AQI is a very important factor for operating the system. Next, a decision-making module has functions to determine the DMS to switch the mode to cooperative control, based on the calculated AQI and Qreq, and to get a suppliable reactive power amount based on Qreq from EMS, and a suppliable reactive power range of the DMS. In addition, if it is determined to switch the DMS to reactive power cooperative control mode, this module transmits the control signal, so that the DMS switches mode to reactive power cooperative control. Then, the DMS provides the required reactive power to an upper layer.

B. Operating Principles

EMS or VMS, as a function of EMS, provides optimal values of the pilot bus voltages in the local areas that are electrically separated

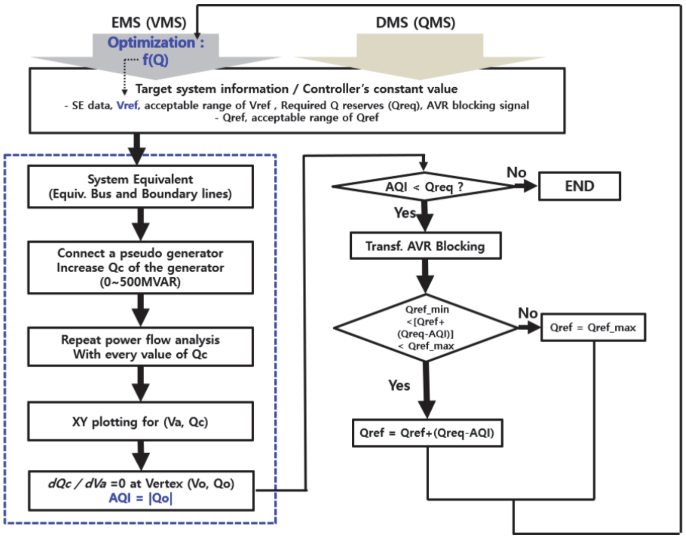

Fig. 7. Main control algorithm of the proposed system.

in the power system. In a normal state, required reactive power reserves are maintained by controlling available voltage compensators in the areas, in order to hold the optimal voltages of pilot buses. Meanwhile, DMS maintains the ordered secondary voltages of 154 kV/22.9 kV transformers by balancing the reactive power resources available in the system and distribution loads. For mutual cooperation between EMS and DMS, a kind of indicator to measure the current reserves of reactive power in the upper transmission area should be needed. By this indicator, the proposed system can calculate the current reserves of reactive power and needed reactive power supplied from DMS, if available. Then, the DMS will decide to supply the amount of reactive power available in the lower distribution area. At the moment, DMS converts the amount of reactive power into the voltages in order to update the pilot bus voltages, as shown in Fig. 5. Again, VMS in the upper transmission area controls the reactive power resources in the area, so that the updated pilot bus voltages can be maintained. At that time, the lower distribution area below 22.9 kV is considered a large reactive power resource that is operating in the mode of automatic reactive power regulation (AQR mode). The proposed cooperative control system takes complete charge of performing the above-mentioned action.

1) Index for reactive power (Q) reserves in an area (AQI)

As described in the above section, it is very important to have a kind of index to measure how much Q reserves currently remain in the area. Fig. 6 shows the method to calculate the reserves, that is the AQI mentioned above.

Firstly, the targeted area should be reduced equivalently to a single bus with the remaining boundary transmission lines, which are connected to the other areas. Then, a pseudo generator is connected to the equivalent bus to raise the reactive power gradually with combination of the bus voltage, followed by the repeated power-flow analysis (Q–V analysis). Finally, a curve can be obtained as represented in Fig. 6. In the curve, the distance between the vertex point of the curve and horizontal axis is the magnitude of AQI that we are interested in. This is the current amount of reactive power reserves in the area.

2) Main control algorithm

Fig. 7 shows the main algorithm of the proposed control

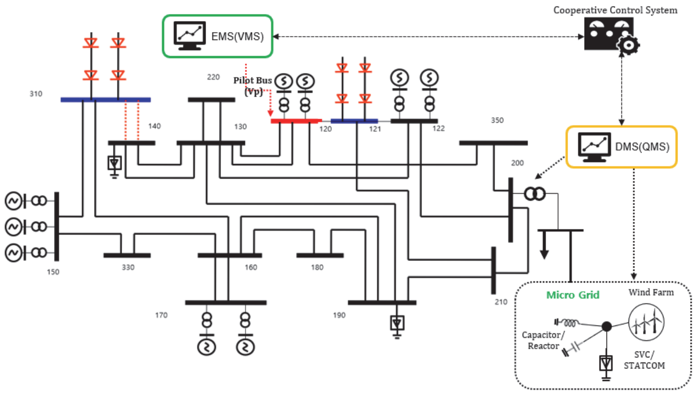

Fig. 8. A Jeju power system for simulation study.

TABLE 1

System Summary

Classification	Value
Real power from HVDC Transmission Area	150MW
Total real power generation	310 MW
Total reactive power generation	110 MVar
Micro Grid area	(BUS 200)
Total real power generation	10 MW
Total reactive power generation	6.5 MVar

system. The left part in the dotted box in Fig. 7 represents the flow chart of how to calculate the AQI. If the current AQI is greater than or equal to the required reactive power (Qreq), which is calculated by EMS, the cooperative system will not operate. However, when AQI is less than the calculated reserves, firstly the system blocks the operation of the transformer's AVR, in order to not control the voltage. If QMS in the DMS has the capability to supply the amount of reactive power (AQI-Qreq), the Qref value will be updated to the value of [Qref+(Qreq-AQI)]. Otherwise, the value of Qref is set to the maximum available reactive power of Qref-max. Then, QMS controls the reactive power resources coordinately in the distribution system, so that the amount of reactive power, Qref, is provided to the upper transmission system. Finally, the proposed system updates the value of Vref resulting from executing the optimize function of EMS, as shown in Fig. 7.

IV. Simulation Results

In this section, in order to validate the proposed system including the control algorithm and the effectiveness of cooperative controls between EMS (VMS) and DMS, the Jeju power system was selected for simulation, as shown in Fig. 8. Four generators out of 10 are participated under the control of VMS, while DMS controls the reactive power generations in the area of the secondary side of Bus 200, as shown in Fig. 8. TABLE 1 summarizes the system description for simulation. The Micro grid in the system consists of a small wind farm, a capacitor/reactor, and a STATCOM.

Fig. 9 shows the simulation results of pilot bus voltages controlled by VMS only, and by coordinative control of VMS and EMS. The result of without control is also displayed for comparison. For clear understanding of the control effects by VMS and DMS coordination, a total 90 MVar of reactive loads are added at the time of 100 seconds in the simulation. As can be seen in the lower line in the graph, in the case of without control, the pilot bus voltage did not recover to the reference voltage, due to the lack of reactive power resources in the system. However, if the VMS with four generators under control is applied in the system, the voltage can be recovered higher than before, as shown by the dotted line in the middle of graph. Under VMS and DMS coordination, the pilot bus voltage was finally recovered to the reference voltage we designated, as can be seen by the solid line in the graph. If the system reaches the point of no reactive power resources remaining in the system, when a severe disturbance occurs, AQI catches the point exactly, so that the coordinative mode begins.

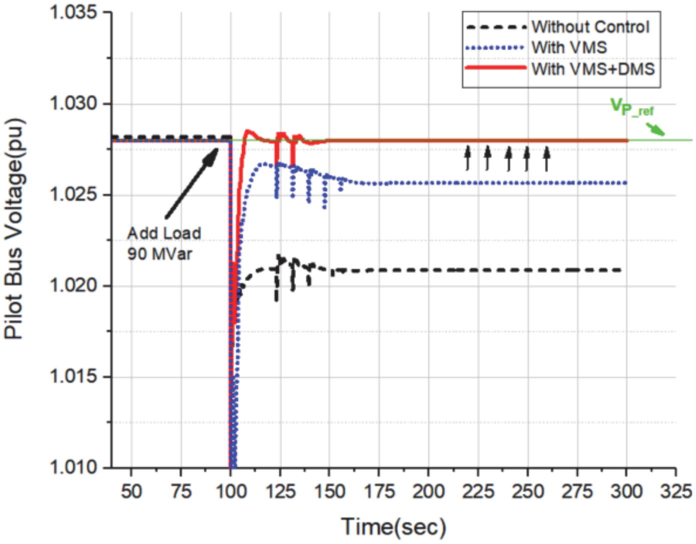

Fig. 9. Comparison of pilot bus voltages with and without coordinative control (for the case of reactive load change).

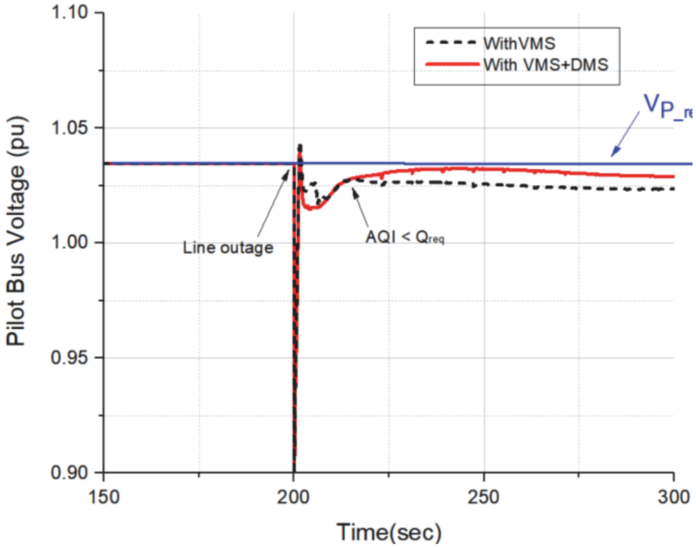

Fig. 10. Comparison of pilot bus voltages with and without coordinative control (for a line outage contingency).

The surplus reactive power in the Micro Grid (Bus 200), even if the amount is very small, can support the upper transmission area. Then, the result is represented as the voltage form of pilot bus. Fig. 10 shows more clearly the response of coordinative control in the case of double line outages of the Jeju system. The dotted line in the Fig. 10 represents the case of VMS only, while the upper solid line

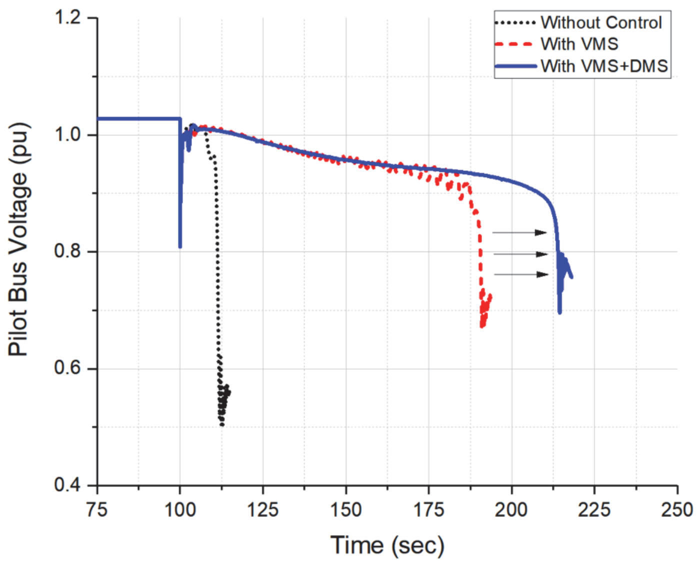

Fig. 11. Comparison of pilot bus voltages with and without coordinative control (for the case of voltage collapse).

represents coordinative control. Around the time of 210 seconds, the AQI decided to accept the surplus reactive power from the distribution area. At that point, AQI became smaller than the required reactive power of the area, as shown in the graph. Through these simulation cases, we could verify the effectiveness of the proposed control system.

Finally, the proposed cooperative control system can also enhance the voltage stability of the system, like VMS. A very severe contingency including a generator outage and load increasement was applied to the system, in order to verify the contribution of the proposed system. As can be seen in Fig. 11, voltage collapse occurred after this severe contingency. As represented by the dotted line in Fig. 11, the VMS expanded the collapse time more than that of the without control case. However, the proposed system made it longer than VMS, even though the amount of time is not so much. Conclusively, a system operator can have more time to take action for this kind of emergency.

V. Conclusion

In this paper, a coordinative control system between EMS (VMS) and DMS to utilize the surplus reactive power in a distribution system was proposed, and its performance proven through simulation. By the proposed system, the voltage quality in transmission area could be constantly maintained in normal state. Also, for the contingency case, such as a line outage, and for the abnormal state, like intentional increase of reactive loads, the proposed system has played an important role in enhancing the voltage stability of the whole power system, as given in the previous section. Furthermore, we expect that the system makes a great contribution to prevent the voltage collapse of the power system in the area, by extending the collapse time longer than that of the without control system, as shown in Fig. 11. Additionally, the proposed system will be properly used for the situation of high penetration ratio of inverter-based resources (IBR). The voltage of Point of Interconnection (POI) can be maintained at the desired value by the system we proposed. However, more in-depth study is needed to implement it in the real field. For example, the method of exact tuning of parameters in the control system should be developed, and more real time simulations are needed to verify the performance of the system by using Hardware-In-the-Loop test, before installing it in a real power system.

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