ANALYSIS OF PRACTICAL ISSUES IN DEVELOPMENT OF VOLTAGE CONTROL SYSTEM FOR LOW VOLTAGE DC DISTRIBUTION SYSTEM

Phi Hai TRINH
Kookmin Univ. – Republic of Korea
trinhphihai@gmail.com

Hector Cho
Kookmin Univ. – Republic of Korea
xeltic@naver.com

Van Thinh HUYNH
Kookmin Univ. - Republic of Korea
huynhvanthinh0512@gmail.com

Il-Yop Chung
Kookmin Univ. – Republic of Korea
chung@kookmin.ac.kr

Seok-Woong Kim
KEPCO – Republic of Korea
sw.kim@kepco.co.kr

Juyong Kim
KEPCO – Republic of Korea
juyong.kim@kepco.co.kr

ABSTRACT

This paper focuses on the low voltage direct current (LVDC) distribution system that has been developed and implemented in Gochang Power Testing Center located in Joennam Province, South Korea by Korea Electric Power Corporation (KEPCO). Low-voltage distribution can suffer voltage regulation issues because of voltage drop in distribution lines. This paper presents the implementation of the hierarchical control algorithm to coordinate multiple AC/DC converters and multiple distributed energy resources (DERs) for LVDC distribution system using multi agent system (MAS) concept. In addition, the practical issues in development of voltage control system such as failure of communication or time delay issues are highlighted in this study. The paper also shows the hardware and middleware configuration of the agent manager, local agent and power system simulation program. The performance of the analysis of voltage control system is demonstrated with the practical cases in Gochang Power Testing Center.

INTRODUCTION

Recent studies have shown that Low Voltage Direct Current (LVDC) distribution system are more economical than traditional alternation current (AC) distribution system in certain circumstances **[1-2]**. The most common advantage of LVDC system is that DC systems can easily connect different types of DC sources without synchronization procedure **[3]**. However, compare to MVAC distribution system, voltage regulation is a significant issues on planning and operation in LVDC distribution system. The main objective of voltage regulation is to supply electricity within a suitable voltage level to all power consumers and then to ensure system stability. The range of voltage range is generally ±5% of the rated voltage **[4]**

There have been many studies on voltage control methods in LVDC distribution system. Authors in **[5-7]** focused on the small-scale DC system with limited service areas using the local voltage control by using DERs with droop control method to control the common bus voltage on DC distribution system while the authors in **[8-9]** proposed the hierarchical voltage control method for LVDC distribution system for both topologies radial and loop-type networks that applied distributed control scheme based on multi agent system (MAS) concept. The main idea of the proposed study is to design the MAS-based voltage control algorithm to coordinate the main AC/DC converters that are hosted by utility and multiple Photovoltaic generators (PVs) that are hosted by the owners. By using this control algorithm, the utility can negotiate with the customers using their excess power to supply back for the LVDC distribution system. The completion of coordinated control between AC/DC converter and DERs are elaborated in **[8-9].**

In 2015, KEPCO launched a research project to develop an LVDC distribution system testing facility in the Gochang Power Testing Center located in Joenam Province, South Korea. Figure 1 shows the LVDC testing simulator in Gochang, it contains many kinds of DER such as PVs, wind turbines (WTs), BESSs, diesel generators (DGs) as well as AC and DC loads. All the DERs and loads are connected to the network via power electronics devices.

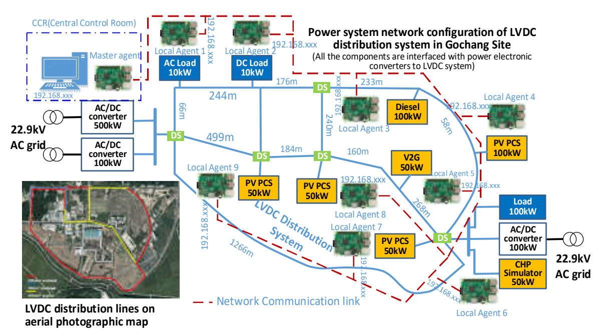


Figure 1. Configuration of 1.5kV LVDC testing simulator and the architecture of MAS implementation in Gochang South Korea

This paper briefly explains the overall voltage control algorithm using MAS **[8-9]** and the implementation of the voltage control method through embedded systems using microcontroller, the design of hardware and middleware of agents. This paper also proposed the MAS power management system (MAS-PMS) that replaces the conventional energy management system (EMS). By using the microcontroller, we can reduce the cost of the system integration and simplify the system structure. We design the distributed control system using MAS with multiple microcontrollers and data exchanges between them using relevant communication. In this paper, we also analyses the practical issues in development of voltage control system using practical experimental system.

VOLTAGE CONTROL IN LVDC DISTRIBUTION SYSTEM

Voltage regulation is an important issue in the design and operation of distribution system. The objective of voltage regulation is to maintain the voltage profiles of the distribution system within a normal range. Reference **[8]** focused on the voltage control in radial LVDC distribution system while reference **[9]** proposed the voltage control in multi-terminal LVDC distribution system. The authors provided a systematic approach for the voltage control in LVDC distribution system including multiple DERs as well as main AC/DC converters. The short explanation on the overall control process and how to calculate the control commands of DERs and AC/DC converters in multiple network topologies has been mentioned in subsequent subsection.

Overall voltage control process based on multi-agent system

In this sub-section, we explain the control hierarchy of the proposed system and communication configuration between multiple agents for common task. The detail of control procedure are as follows

Step 1: In normal state, all the agents operate in monitoring mode and measure local voltages. If the measured voltage exceeds the normal limits, the local agents inform the master agent of the voltage problem via request message with the voltage deviation (ΔV_k).

Step 2: The master agent requests for voltage control proposals to all DER agents to update power system information with the latest values. The process begins with issuing a request for proposal (RFP)

Step 3: Local agent responds to the RFP by sending their collected information including bus voltage, line current, power margins of the DER, and Jacobian matrix information.

Step 4: After receiving the collected information from local agents, master agent defines the control sequence and calculates the voltage control commands for AC/DC converters and DERs.

Step 5: The master agent assigns the tasks to the selected converters and DERs agents. If the voltage compensation is not enough due to any errors, the voltage control process is repeated until the amount of voltage deviation become less than a certain threshold.

Computation of voltage control commands

The main AC/DC converter commands will be calculated based on the structure of network topology. For the radial system with one AC/DC converter connected to the grid, the AC/DC converter control command can be calculated by using equations (1)-(3)

$$\Delta V_{i\text{-}1} = \frac{f_1(\Delta V_i) + f_2(\Delta V_i)}{2V_{i\text{-}1}^{old}} \tag{1}$$

Where

$$f_1(\Delta V_i) = -\left(V_{i\text{-}1}^{old}\right)^2 + V_{i\text{-}1}^{old}.\Delta V_i - P_{i\text{-}1,i}.r_{i\text{-}1,i} \tag{2}$$

$$f_2(\Delta V_i) = \sqrt{\left[\left(V_{i\text{-}1}^{old}\right)^2 - V_{i\text{-}1}^{old}.\Delta V_i + P_{i\text{-}1,i} \times r_{i\text{-}1,i}\right] + 4\left(V_{i\text{-}1}^{old}\right)^3.\Delta V_i} \tag{3}$$

V_i^{old} is the voltage at bus *i*-th before control, $r_{i,i-1}$, $P_{i-1,i}$ are the line resistance and line power flow between the (*i*-1)-th and *i*-th buses, respectively and ΔV_i is the voltage variation at the target bus. These values can be measured by the local agent. It can be noted that in order to compensate the voltage at the target bus as much as ΔV_i, we need to change the voltage at (*i*-1)-th bus as ΔV_{i-1}. If we apply (1) up to the first bus where AC/DC converter installed using backward sweeping method, we can finally obtain the voltage command of the AC/DC converter.

The equations (1) - (3) were analyzed from radial LVDC distribution system with only one main AC/DC converter **[8]**. Therefore, they cannot be applied for the loop multi-terminal LVDC distribution system.

The authors in **[9]** proposed two methods to calculate the AC/DC converter control commands in loop multi-terminal LVDC distribution system: (1) iterative numerical computation method and (2) linearly approximated circuit analysis. The results analysis in **[9]** indicate that using method 1 is more suitable to compute the AC/DC converter command as compared to method 2 in term of accuracy, power losses and processing time. Therefore, in this paper we apply method 1 to obtain the control command of the AC/DC converters for multi-terminal LVDC distribution system.

The DER commands are calculated based on the voltage sensitivity factor (VSF). The VSF is defined as the effect of power variation control of the DERs on the voltage compensation of a specific bus. We can also determine the control priority of DERs based on the VSF values. The VSFs can be obtained from the Jacobian matrix of the LVDC distribution system. We can define the VSF between the voltage at the *i*–th bus and the power injection at the *j*-th bus as

$$[VSF]_{ij} = \frac{\Delta V_i}{\Delta P_j} = [J]_{ij}^{-1} \tag{4}$$

Where J is the Jacobian matrix corresponding to derivation of the active power from the bus magnitude.

MULTI AGENT SYSTEM DESIGN

Agent design

The design of multi agent system should meet two conditions: (1) modularity, the software of each agent should be modular design, the changing of the first module must not effect to the others and (2) total size of MAS must be as small as possible to be easily integrated in other energy management system (EMS) with a small effort. Figure 2 shows the agent architecture design, it consists of two main parts: voltage control algorithm and communication parts. The voltage control algorithm contains the computation, agent functions and decision making whereas the communication part consists of three sub-parts named as middleware, operation system (OS) and hardware (H/W), the middleware has a function for the agent communication.

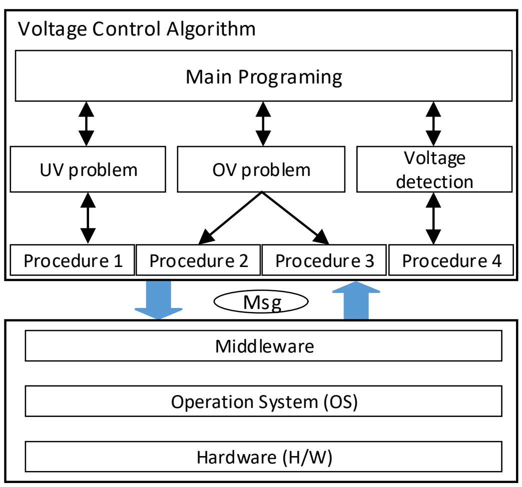


Figure 2. Agent architecture design

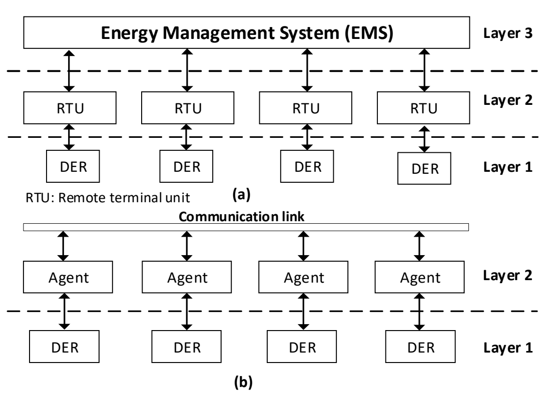


Figure 3. The comparison between: (a) conventional EMS and (b) proposed PMS based on MAS

Figure 3 compares the conventional energy management system (EMS) to the proposed MAS power management system (MAS-PMS). The MAS-PMS is considered as the updated version of the conventional EMS with simpler design and operation. The functions of layer 3 in the conventional EMS are added to layer 1 in MAS-PMS. Therefore, the communication between agents is required in the proposed architecture.

Middleware design

In the proposed system, the communication between agents is one of the most important factor. As shown in figure 2, the middleware consists of some general functions or actions that can be used for communicating and integrating agents. These functions can manage the connection between agents and handle the request and response messages between them. In this proposed MAS architecture, the middleware is developed using C++ language that can support object-oriented technique. The C++ builder development environment provides many components for users, one of the components, transmission control protocol/internet protocol (TCP/IP) is utilized our middleware designing.

Message exchange process

The master agent makes the decision and response to the local agent accordingly. The black arrows and numbers in figure 4 show the request/response procedure between master agent and local agent through middleware. The detail is described as follow

Step 1: master agent sends request to local agent through communication middleware to obtain local information from the local agent. Write Request and Read Request type are named as (1) and (2) in figure 4.

Step 2: after receiving the request event from master agent, the local agent generates a response event through the communication middleware. Similarly, the Write Response and Read Response types are named as (3) and (4) in figure 4.

In the opposite side, the red arrows and numbers in figure 4 explain the message exchange process that local agent sends request to master agent and receives a response event from master agent.

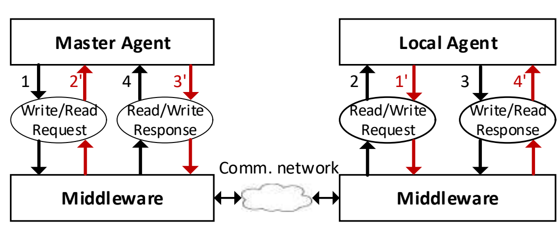


Figure 4. Request/Response procedure of master agent sending event to local agent and local agent sending event to master agent.

PRACTICAL ISSUES ANALYZATION FOR LVDC DISTRIBUTION SYSTEM

As we mentioned in this paper, our voltage control algorithm using MAS-based has been implemented in Gochang Power Testing Center, the implementation has been faced some practical issues that make the voltage variations not improved after applying the proposed voltage control algorithm. In this section, we focus on three main issues that largely effect the control performance and economic factors.

The first issue is the failure of communication link or the failure of agent connection result in the bad data collection, in the implementation of MAS in Gochang Power Testing Center, the data measurements collected from agents are different from the true values. The data collections from several agents care offset by the constant values. This problem occurs because of the failure in measurement from the devices. Furthermore, the failure of communication links between agents also causes the losses of data. These errors effect directly the results of voltage control commands of AC/DC converters and DERs. These issues can be solved by using some state estimation methods such as Maximum Likelihood Weighted Least Square state estimation or distributed state estimation under multi-agent system (MAS) based algorithm.

The communication delay issue is also one of the most important practical issue in LVDC distribution system. The delay time includes computation delay, communication delay and control action delay that lead the voltage variation, hence, affecting directly the voltage control performance. To solve this problem, an operation planning can be applied using predictive method that will forecast the overall voltage profiles then plan the control algorithm for overall system using forecasting data.

Another issue on implementing the system is that the consideration of quantity of local agent in a large scale LVDC distribution system. Because of the economic issues, we have to select a limited number of locations for local agent by taking care of negligible effect on the voltage control performance. Therefore, a concept of "virtual node" is necessary to reduce the number of agent devices. The aim of this concept is to estimate the voltage which is not monitored by local agents considering negligible effect on results. In [8], we proposed this concept and proved that the control commands error are less than 5% which does not affect too much to the voltage control algorithm.

SYSTEM IMPLEMENTATION AND RESULTS DISCUSSION

To verify the effectiveness of the proposed LVDC control system, we implemented the test cases for LVDC distribution system in Gochang Testing Simulator Centor based on MAS with C++ programing environment. The LVDC power system model is depicted in figure 6, we used switches to change the network topologies with radial and loop-type multi-terminal network. The main AC/DC converter(s) interconnected to the 22.9kV AC grids.

It is assumed that there are three photovoltaic generators (PVs), BESS, diesel generator (DG) and wind turbine generator (WT) connected to the LVDC distribution system as shown in figure 6. Each DER has power margins that can generate up to 50kW for PV and 100kW for other DERs. Loads are distributed over the distribution lines as shown in the figures. The control system comprises one master agent and eight local agents located in each bus.

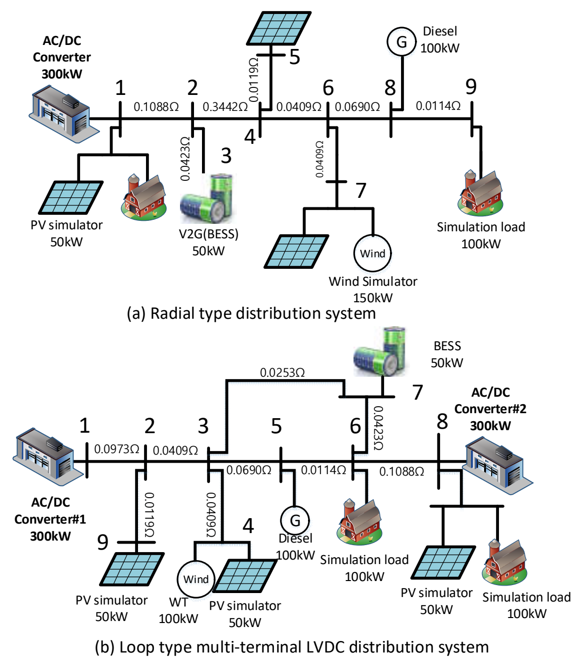


Figure 6. LVDC distribution system in Gochang Testing Simulator in (a) radial type network and (b) loop-type multi-terminal system

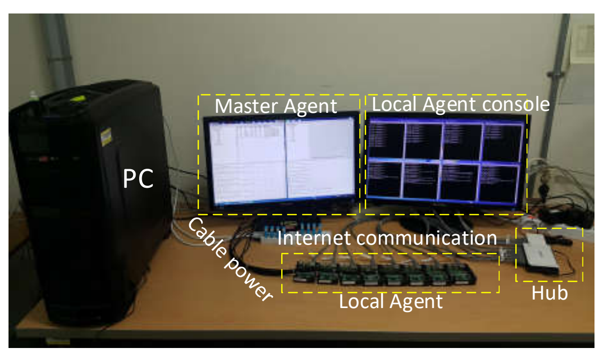
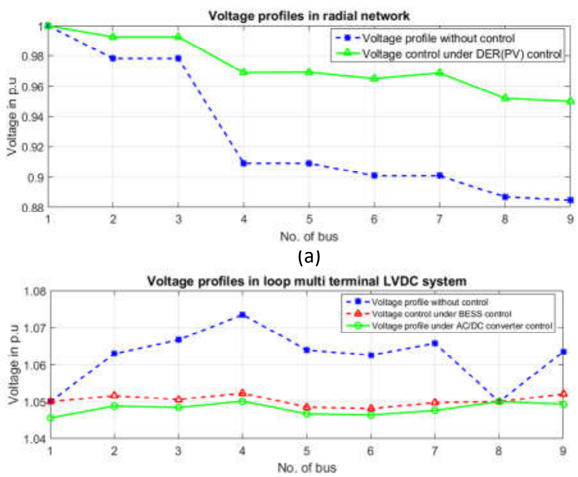


Figure 7. Implementation of MAS hardware for voltage control in LVDC distribution system

Figure 7 shows the test hardware set-up with agent devices and PC based management system. The local agents connect to DERs via the serial port. The master agent and local agent communicate to each other through the internet communication link. The voltage control commands will be generated by the master agent through the collaboration between local agent and master agent. These results of the agent can be evaluated by the local agent console based management system.



(a) (b)

Figure 8. Results of voltage control in implementation

Figure 8 shows the results of voltage responses before and after the control actions for radial and loop network topologies. Figure 8a shows the under voltage problem in radial network, the blue line represents the under voltage problem without voltage control and the green line shows the voltage responses after the DER (PV) control. Similarly, figure 8b shows the over voltage problem in the loop multi-terminal LVDC distribution system. The blue line represents the over voltage problem without voltage control while the blue line shows the voltage response after BESS control. However, the overvoltage problem still exists at bus 3, 4 and 9. Therefore, the AC/DC converter control has been applied to solve the problem as shown in the green line in figure 8b.

CONCLUSION

This paper has presented the voltage control scheme for LVDC distribution system using coordination control between AC/DC converters that hosted by utility and multiple DERs that are hosted by the owners based on MAS. In this paper, we also proposed the multi agent system designing in term of agent system operation, middleware design and hardware design. The implementation has been faced some practical issues, we proposed the solutions to stop the problems. The results demonstrated the success of the proposed voltage control method under different conditions and system configurations.

Acknowledgments

This research was supported by Korea Electric Power Corporation (R18XA06-19) and by the Ministry of Science and ICT, Korea, under the ITRC(Information Technology Research Center) support program(IITP-2018-0-01396) supervised by the IITP (Institute for Information & communications Technology Promotion) .

REFERENCES

[1] Starke, M.; Tolbert, L.M.; Ozpineci, B. “AC vs DC distribution: A loss comparison”. *Transmission and Distribution Conference and Exposition*, IEEE/PES, 2008, Chicago, IL, USA, April 22-24

[2] Whaite, S.; Grainger, B.; Kwasinski, A. “Power quality in DC distribution systems and microgrid”. *Energies* 2015, 8, 4378-4399; doi: 10.3390/en8054378

[3] Kim, J.; Kim, J.; Cho, J.; Song, I.; Kweon, B.; Chung, I.; Choi, J. “Comparison between Underground Cable and Overhead Line for a Low-Voltage Direct Current Distribution Network Serving Communication Repeater”. *Energies* 2014, vol.7, no.3, pp.1656-1672

[4] Std, ANSI C84. 1-2011. “American National Standard for Electric Power Systems and Equipment-Voltage Ratings (60 Hertz) 2011”. Avaliable online: *https://www.nema.org/Standards/ComplimentaryDocuments/Contents-and-Scope-ANSI-C84-1-2011.pdf* (accessed on 20 September 2015).

[5] Hrisheekesha, P. N.; Sharma, J. “AI applications to distribution system with distributed generation”. *International Journal of Computer Applications*, 2010**,** *1*, no. 14, pp. 38–42

[6] Viawan, F.A.; Karlsson, D. “Voltage and reactive power control in systems with synchronous machine-based distributed generation”. *IEEE Trans. Power Del.*, 2008, 23, no. 2, pp. 1079–1087.

[7] Hamad, A.A.; Farag, H.E.; El-Saadany, E.F. A Novel Multiagent Control Scheme for Voltage Regulation in DC Distribution System. *IEEE Transaction on Sustainable Energy*, 2015, 6, No 2. pp.534-545

[8] Trinh Phi Hai, Hector Cho, Il-Yop Chung, Hyun-Koo Kang, Jintae Cho, and Juyong Kim. “A Novel Voltage Con-trol Scheme for Low-Voltage DC Distribution Systems using Multi-Agent Systems,” *Energies*, vol.10, no.1, Jan. 2017, (article number:41).

[9] Trinh Phi Hai, Il-Yop Chung, Jintae Cho and Juyong Kim. “Coordinated voltage control scheme for multi-terminal low-voltage DC distribution system”. *Journal of Electrical Engineering and Technology* 13(4):1459-1473 DOI: 10.5370/JEET.2018.13.4.1459