DESIGN AND EVALUATION OF VOLTAGE CONTROL TECHNIQUES BY HIERARCHICAL COORDINATION OF MULTIPLE POWER CONVERTERS IN LOW-VOLTAGE DC DISTRIBUTION SYSTEMS

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ABSTRACT

This paper focuses on voltage control schemes for low-voltage DC (LVDC) distribution systems that has been studied for electrification of rural sides in South Korea. Telecommunication repeaters on mountain tops can be a good application for LVDC systems because it needs DC power rather than AC and low-voltage distribution can reduce the operation and maintenance costs for distribution network operators (DNOs). However, low-voltage distribution can suffer voltage regulation issues depending on the size of the systems. This paper presents the design concept of multi-agent based hierarchical control schemes for distribution voltage regulation and evaluation of the control performance by simulation studies.

INTRODUCTION

Low-voltage DC (LVDC) distribution systems have been evolving into an interesting topic in the field of distribution system studies these days [1]. A few months ago, a new project on LVDC distribution systems has been launched by Korea Electric Power Corporation (KEPCO). The main objective of the project is to replace medium voltage AC (MVAC) distribution systems with 1,500V LVDC distribution systems for rural areas. The project also targets to develop economic and effective models for LVDC distribution systems [2].

One of the promising candidates for LVDC distribution systems in South Korea is the distribution systems for wireless telecommunication repeaters scattered in rural areas as shown in Fig. 1. There are several advantages in this application. First of all, telecommunication repeaters are usually notorious for poor power factor and efficiency. Because most loads in the repeater systems are IT devices that need DC power rather than AC, LVDC distribution can improve energy efficiency. Second, some of the existing MVAC distribution lines using aerial bundled conductor (ABC) cables have been worn out through years so that they are vulnerable to high impedance faults by contacting with tree branches and leaves. Therefore, it is about the time to replace ABC distribution lines with new ones. Lastly, DC distribution lines can integrate renewable energy resources such as photovoltaic (PV) systems or energy storage systems (ESS) easily compared to AC distribution lines. DC distribution systems have advantages to integrate DC generator to DC loads.

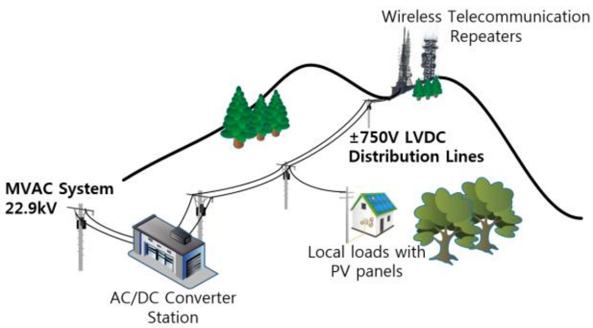

Fig. 1. Electrification for telecommunication repeaters on mountain top using LVDC distribution system

However, despite of optimistic point of views, the voltage regulation of the 1,500V LVDC distribution systems can be a significant issue compare to conventional MVAC distribution systems which are rated at 22.9 kV in Korea. Because of low-voltage distribution, the increased line currents can cause significant voltage drops and energy losses compared to medium-voltage systems [3]. The over and under voltage problems can limit maximum transferrable power to loads and hosting capacity of distributed energy resources. Therefore, voltage control in LVDC distribution system is a very important issue to improve power quality and system size extension.

In this paper, we propose voltage control methods considering effective hierarchical coordination between the main AC/DC converter and distributed energy resources or storage systems scattered in the system. In order to implement flexible coordination between multiple control units, we consider multi-agent system (MAS) technology that is an emerging modern technology based on agent-oriented programing (AOP) [4]. By using MAS technology, we can design a novel cooperative protocol to provide a proper voltage control for LVDC distribution system.

VOLTAGE CONTROL METHODS IN LVDC DISTRIBUTION SYSTEMS

Voltage regulation is a significant issue on a planning and operation in most distribution networks because it is related to the quality of electricity distribution service and also energy losses in the systems. Therefore, DNOs are required to maintain the distribution voltages within suitable ranges, which is generally set to ±5% from the rated voltage. However, compared to medium-voltage cases, LVDC distribution systems are more vulnerable to voltage regulation issues.

Fig. 2 illustrates a LVDC distribution system for communication repeaters in rural mountainous areas. The major design objectives for these distribution systems are to extend the system size and to host more distributed energy resources (DERs) in the systems. Therefore, we want to develop an efficient and economic voltage control system for a LVDC distribution system widely stretched to secluded areas. To this end, this paper proposes a multi-agent system (MAS) based hierarchical voltage control system with coordinated computation and decision making procedures.

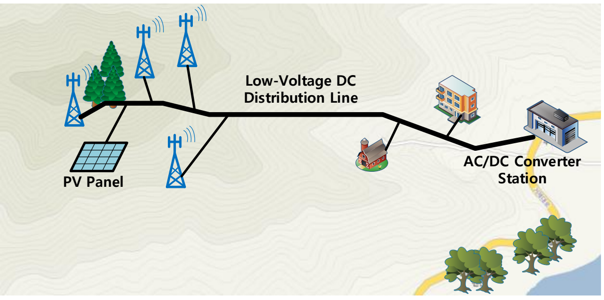

Fig. 2. Conceptual drawing for possible LVDC distribution systems for telecommunication repeaters

Hierarchical Voltage Control System

Fig. 3 shows the one-line diagram of a LVDC distribution systems with voltage control system. The voltage control procedure consists of two stages. In the first stage, the AC/DC converter is mainly responsible for voltage support of the distribution lines within the normal range because the output voltage control affect the system-wide voltage profile.

If the AC/DC converter cannot control the bus voltages sufficiently, the DERs can support voltage to normal range by supplying electric power to neighbouring loads in the second stage. On the other hand, DERs can cause overvoltage problems especially for light loading conditions. Therefore, relevant coordination between the AC/DC converter and DERs are very important.

Fig. 3 also shows that multiple agents are connected through communication links to share the system information and transfer the control commands. For efficient coordination control, we defined control hierarchy between agents. First, the master agent is the leader in MAS-based control environments and controls the output voltage of the main AC/DC converter. The major functions of the master agent are as follows: 1) to collect power system data from local agents; 2) to calculate load flow analysis for overall systems; 3) to calculate the precise control command of the AC/DC converter; and 4) to find the optimal combination of multiple DERs and dispatch the control command to local agents.

Second, local agents are 1) to detect and estimate power system parameters by refining local information and communication with other agents and 2) to transfer the collected information to the master agent and follow the control command from the master agent. For economic point of view, we do not have to install local agents to all the nodes in the distribution lines but can select some locations for local agents. Then, voltage estimation algorithms are needed for the points that are not monitored in the distribution system.

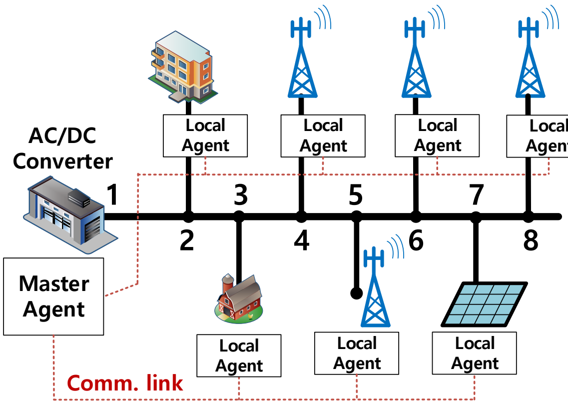

Fig. 3 Single-line diagram for the conceptual LVDC distribution systems in Fig. 2

There are previous researches into application of MAS-based voltage control for distribution systems [5-7]. Especially, references [6] and [7] presents pioneering jobs about the related issue in DC distribution systems. However, reference [6] ignored line losses that can be significant in LVDC distribution system. Reference [7] derived simplified voltage sensitivity factors but can be applied only to radial distribution system. In our system, local agents participate to build the Jacobian matrix of the distribution system together. For example, local agents calculate corresponding rows of the Jacobian matrix and send the information to the master agent. Then, the master agent calculate overall voltage sensitivity factor with the collected information.

Fig. 4 illustrates the flowchart of the coordination control. The details of the control procedures are as follows.

Step 1: In normal condition, local agents monitor or estimate local node voltages. If the node voltages exceed normal limits, the agent informs the master agent of the voltage problem.

Step 2: The master agent requests for all local agents to update power system information with the latest values. Then, local agents send time-synchronized power system data including bus voltages, active power margins and information of Jacobian matrix.

Step 3: The master agent runs load flow analysis algorithm, which can produce important data for voltage control. From the results of load flow analysis, the master agent go through control stages 1 and 2 in Fig. 4. The participation of DERs in voltage control depends on the voltage sensitivity factors (VSF) that represent the relationship between a specific bus voltage change and active power injection by a specific DER. Normally, the VSFs can be obtained by inverse of the Jacobian matrix.

Step 4: Finally, the master agent determines the control commands for the main AC/DC converter and the DERs. These commands are delivered to corresponding units via communication links.

Fig. 5 shows simulation results that shows the control performance of the proposed control method. The line graphs represent the bus voltages of the LVDC distribution system. The horizontal axis represents the bus numbers illustrated in Fig. 3. The simulation conditions are based on the practical distribution system data of South Korea like Fig. 2 but the distribution line lengths and load sizes are modified a bit to show the control performance clearly.

In Fig. 5, the blue line represents the voltages in per unit without voltage control. It shows that the voltages exceed the normal operating range from 0.95 p.u to 1.05 p.u. The minimum voltage in this case is about 0.84 p.u. The red line shows the voltages after controlling the main AC/DC converter (after running control stage 1 in Fig. 4). However, there are still under-voltages in the red line. Finally, the black line represents the voltages after applying both the AC/DC converter control and DER power injection (after running control stage 2).

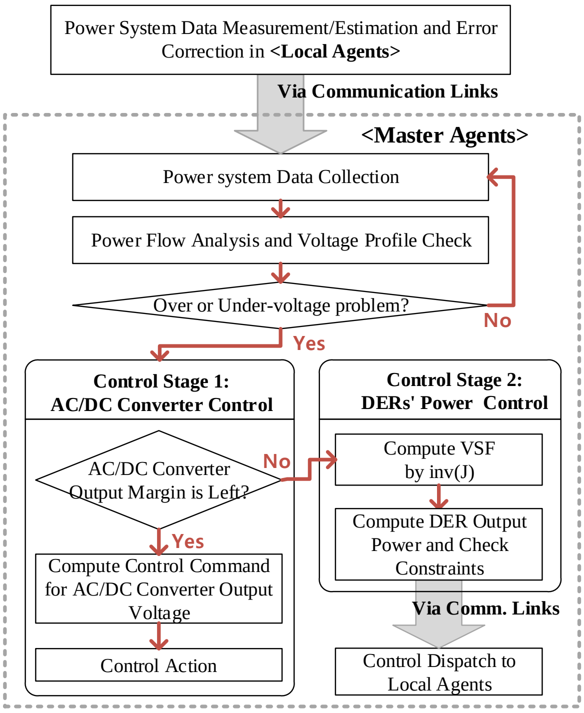

Fig. 4. Flowchart of the proposed voltage control method for LVDC distribution systems

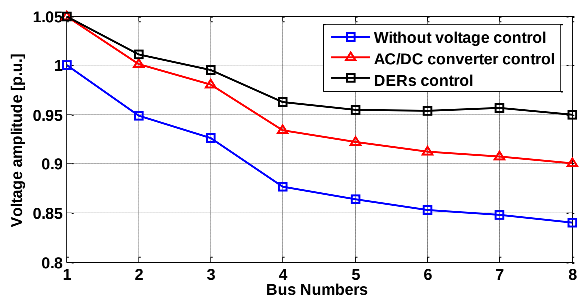

Fig. 5 Simulation results of the proposed voltage control method using MATLAB

PROTOTYPE SYSTEM FEATURES

Fig. 6 shows control system layers and communication links of the developed voltage control system. To realize our control concept economically, we chose 32-bit ARM-based microcontrollers and open-source based real-time operating system named as eCos. The specification of the developed agents is listed in Table 1.

Table 1. Hardware specification for local control agents

Category	Feature
Core	ARM 32-bit Cortex-M4
Speed	180 MHz
RAM size	256 kByte
Flash Size	2Mbyte
Operating System	eCos

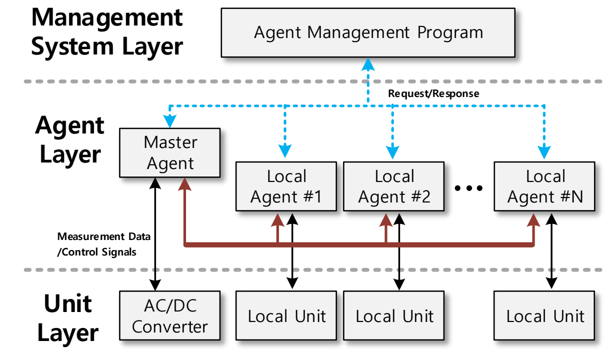

Fig. 6 Control layers and data communication structure in the proposed hierarchical voltage control system

To efficiently implement and manage the agent programs, we modified some part of the eCos codes for our multi agent system. For example, we divide the flash memory into two areas: one for program code execution and the other for flash file system.

We developed the middleware to provide common management service for various OS platforms such as eCos, MS windows or something. Fig. 7 shows a conceptual diagram for the developed middleware. The developed middleware consists of five sub-modules as shown in Fig. 7. ABS (Agent Basic Service) includes common functions for agent program such as start, stop, reset and so on. Our middleware provides two interface modules for application-layer programs such as ACSI (Agent Contraction Service Interface) and AMSI (Agent Management Service Interface). ACSI supports asynchronous communication service for bidding and negotiating between agents. AMSI provide interface for remote management at run time. For example, IP addresses and other setting values can be changed during operation. In addition, all the agents can be started or stopped by human operator using remote PC program.

In the application layer, load flow algorithms and bidding and negotiation algorithms based on contract net protocol (CNP) are implemented.

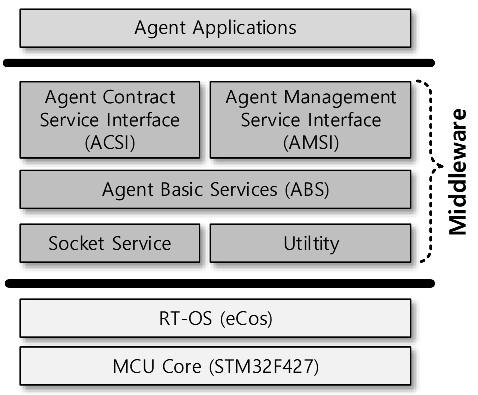

Fig. 7 Functional diagram of middleware for agent systems

CONCLUSION

The voltage profile in distribution system is affected by various conditions such as the output of AC/DC converter and DER units scattered in the distribution system. This paper presented an efficient and economical voltage control method in LVDC system using multi-agent systems. In addition, the details of the developed system hardware and software are also introduced. Especially, we implemented middleware program to interface various operating systems and also to manage local agent at run time.

Acknowledgments

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