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A novel voltage control strategy in collaboration with information technology domains through the holonic architecture

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Abstract: This paper presents a novel framework for voltage control based on holonic architecture, with a priority action of local controllers. The proposed architecture is a hierarchical distributed structure in which two various information technology domains called the energy management system holon and flexible AC transmission system holon are defined. In the proposed structure, a dynamic reconfiguring method for holons is used to reduce the time of corrective actions in the case of emergencies.

Key words: Voltage control, holon, decentralized scheme, smart grid, information technology

1. Introduction

Broadly, there are two reasons to create a national smart grid. First, the current network needs to be upgraded due to deficient and obsolete devices. Second, the benefit of a smart grid is substantial, which engenders refinements in key operating factors [1]. Consequently, it is crucial to put smart technologies into action to achieve effective operation. For one thing, an outage of a line interconnected to a distribution system can significantly change the system voltage profile. In this case, conventional control strategies do not provide suitable ways for dealing with the problem. This interference leads to overvoltage, undervoltage, increase in system losses, and excessive wear and tear of voltage control devices [2]. Therefore, voltage control strategies in the smart grid should be compatible with modern smart activity and equipment in the whole system.

Recently, many investigations have been proposed to introduce a prosperous decentralized framework by which a continuous, timely voltage control takes place throughout power system utilization. For instance, a top-down layered model was introduced in [3], which follows a chain of command called an incident command system in order to achieve a desirable voltage profile. As another example, in the decentralized framework proposed in [4], agents determine the injection of reactive power to the grid resulting in voltage profile improvement. Similar to [4], the authors of [5] presented a distributed multiagent strategy for reactive power management incorporating renewable energy sources. In spite of some particular advantages in the previous voltage control frameworks, there are several setbacks for a smart voltage control strategy to some extent.

According to different smart grid standards, there are two chief features for smart activities to solve a problem. One is the improvement of an undesirable condition in a timely manner, and another is the control actions to achieve a secure condition. In the voltage control strategy, since there are several variables dealing with the voltage control problem, the centralized operating scheme cannot control voltage deviations at an

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optimum point. In addition, the number of controllable variables for a voltage control problem in a smart grid becomes greater than in conventional power systems. For that reason, processing time in a centralized voltage control scheme may increase dramatically. To address the time-consuming voltage control problem, it is necessary to propose a novel architecture capable of handling the voltage level instantly, even if the number of variables has increased. Fortunately, in a smart power grid, there is some potential for using the voltage control not only in a normal state, but also in a contingency. With smart communication and IT technologies in the smart grid, some of the voltage control devices can be handled remotely. This may cause the operation to be less time-consuming. Moreover, through the smart grid concept, a decentralized scheme can be used to determine control actions locally. Indeed, using a multiagent-based structure, the voltage control scheme can be applied to distribution and customer domains of the system.

In this paper, a holonic-based framework is suggested to improve the voltage control strategy. In this structure, when an emergency level is observed by the energy management system holon (EMS-Holon), the head of the related holon sends a corresponding required action through a hierarchy, where it is received by FACTS devices. A desirable level is thus achieved using the approach described in this paper.

2. Principle of holonic structure

The holon is the basic concept of holonic structures. Holons can consist of subholons and they can also be part of a larger one. Consequently, a tree structure is formed in which members work together to achieve a complex goal. This tree-like structure is called a holarchy and is shown in Figure 1. A holarchy is a hierarchy of self-regulating holons that function as an autonomous whole superordination of their parts, as dependent parts in subordination to control higher levels, and in coordination with their local environment [6]. The holonic structure provides information encapsulation in the system and controls access of entities to the information. The idea of a holonic structure is a combination of top-down hierarchical and distributed control structures [6,7].

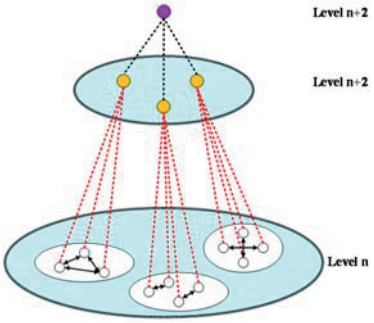

Figure 1. A view of a holarchy.

Three types of internal structures were proposed for holonic multiagent systems [8,9]. In this paper, a specific internal structure of holonic architecture, which is convenient for the smart grid model, is used. In this structure, a holon is a moderated group in which agents lose some parts of their autonomies. One of the agents is designated as the head of the holon and represents the superholon in the external world. The head of the holon can allocate resources to the agents that are inside the holon and can also plan and manage a negotiation between the agents [6,9]. The head of the holon can be determined primarily by two methods: 1) a new agent is created as a head for the lifetime of the holon, and 2) a member of the holon takes the role of a head and accepts the extra duties. In this method, this member of the holon is elected during an election or is predestined for leadership [10].

3. Principle of voltage control strategy

In a voltage control problem, there are many constraints and equations that should be fulfilled totally [11]. The voltage control issue studied here has the following mathematical formulations:

$$\min \sum_{i=1}^{N_B} \left(V_i\left(x,u\right) - V_i^*\right) \tag{1}$$

$$\mathrm{PFC}\ \left(x,u\right) \tag{2}$$

$$\text{subject to } U^{min} \leq u \leq U^{max} \tag{3}$$

where the PFCs describe the relationship of voltage and current of each branch and node. PFCs are formulated in the equations. Further formulations of the voltage control problem are given in [11].

4. Holonic-based voltage control strategy for a power system in collaboration with information technology (IT) domains

To integrate the holonic structure into the voltage control strategy, this paper defines a systematic coherent structure for power system elements as well as IT domains. In this section, first a holonic architecture for software domains is introduced. Then a holonic-based voltage control strategy through voltage controllers of the power system is proposed.

5. A holonic structure for IT domains

From an IT perspective, the transmission grid includes five software domains. These domains are categorized as follows: energy management system (EMS), transmission asset management (TAM), transmission mobile workforce management (TMWM), transmission substation (TS), and transmission field device (TFD). Further information about software domains is described in [4].

Figure 2 illustrates software domains called software holons with their predefined relations. In the proposed architecture, all software entities, databases, and expert systems on the IT level of the transmission grid are assumed as intelligent agents. The whole of the transmission network is assumed as a transmission holon, which is composed of IT subholons. The internal structure of the transmission holon is a federation of autonomous agents. In the proposed structure, a head software agent is adjusted for each holon. In each holon, the head is responsible for establishing communication between software agents inside the holon and also connecting them to software agents in other holons. For example, if a software entity in the EMS-Holon wants to get information from a specific transmission control software, it will connect to the head of the EMS-Holon and send a request for it. The head of the EMS-Holon will send the request to the head of the TS-Holon. The head of the TS-Holon will get the required information from the requested substation control software and send the information through the head of the EMS-Holon to the related entity.

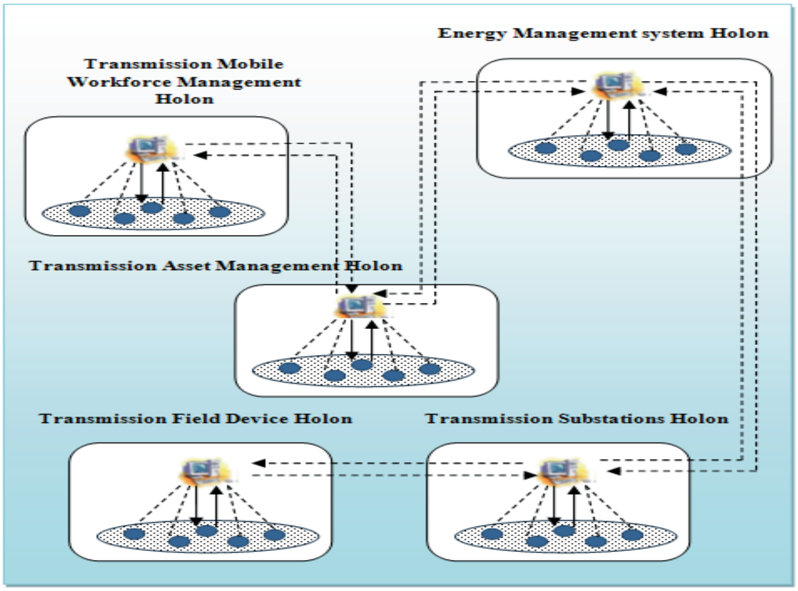

Figure 2. Proposed architecture for the IT infrastructure of the transmission grid.

6. Holonic-based voltage control strategy for the power system in collaboration with the proposed holonic-based IT domains

The EMS-Holon has the authority to control the whole system only in conditions of emergencies. Also, the tracking of voltage level is done in a systematic way by the EMS-Holon.

In the power grid, there are several voltage controllers that act to improve voltage levels. This paper categorizes these elements into power holons called FACTS-Holons. There are several distinctive characteristics provided for the FACTS-Holon. First, the FACTS-Holon incorporates not only the FACTS devices but also other controllable variables, such as LTCs in the LTC-Holon, capacitors and inductors in the COMP-Holon, and FACTS devices in the F-Holon. Secondly, the TS software and TFD software domains superintend subholons within the FACTS-Holon in a collaborative way. Additionally, through the proposed IT structure, the FACTS-Holon communicates with the EMS-Holon in the case of an aberrant voltage level. Thirdly, the TS software domain called the TS-Holon and the TFD software domain called the TFD-Holon receive the reactive support entreaty from their subholons, determine a response action, formulate corresponding action demands, and send them to predefined subholons. In Figure 3 the holarchy design of a power system for voltage control is represented.

Now let us scrutinize the structure of the holonic-based voltage control framework shown in Figure 3 methodically. As shown, there is a subholon called the head of the holon. In this paper, we promote our voltage control strategy on the priority of FACTS emergency actions as the head of the holon. If the FACTS action does not provide a way of dealing with a voltage problem, the other defined subholons in the FACTS-Holon could be a delegate for immediate action. Moreover, there are many communication lines that are perceptibly distinguished. By noting the structure, one can find that there are no extra communications from down holons to the EMS-Holon. As shown in Figure 3, all communication and computation is performed by the IT domains according to the proposed IT architecture. To better describe the idea of holons and subholons, consider how a tree-like distributed structure can be practicable in a power system.

1. The EMS-Holon superintends the FACTS-Holons over the transmission system. The EMS-Holon is

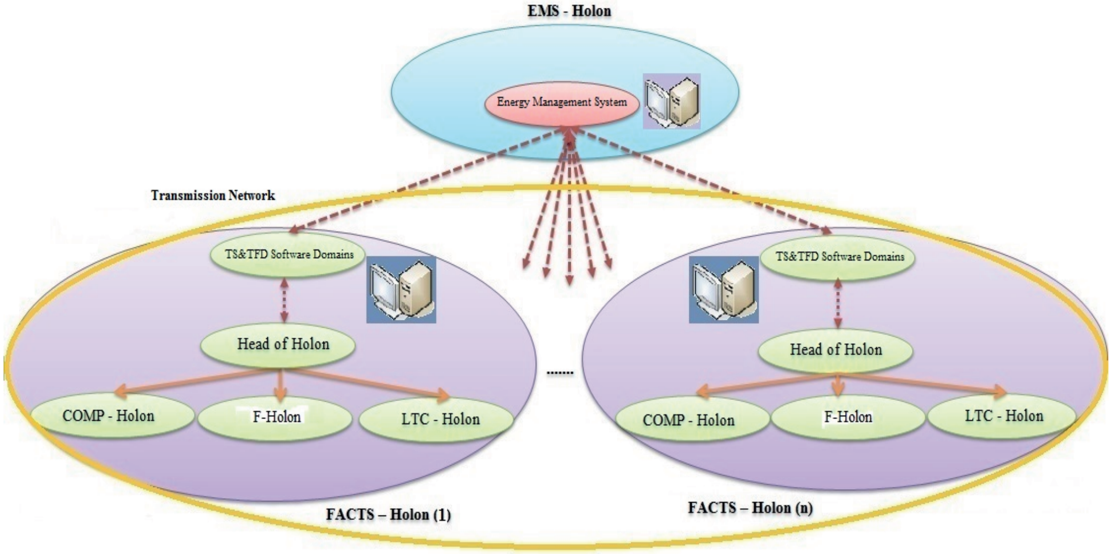

Figure 3. Proposed holonic-based structure for voltage controllers in the transmission grid.

authorized to change the configuration of the FACTS-Holons regarding voltage of buses. Like the FACTS-Holon, the EMS-Holon has computation software to dispatch, send, or receive messages. It constantly computes the voltage of buses in offline mode using information provided in advance.

2. The TS and TFD software domains make an online dispatch in earlier configurations of each FACTS-Holon. In the case of trivial events, because of the predominance of the head position, it can improve the situation in collaboration with the subholons. When the head of the FACTS-Holon detects a critical voltage problem somewhere, it informs the EMS-Holon to readjust configurations for the FACTS-Holons due to decreasing time of operation. Also, the TS and TFD software domains send the loads and subsystems information to the EMS-Holon to make an online dispatch.

3. Using the offline result obtained from software, such as neural networks, the EMS-Holon allocates abnormal buses to the FACTS-Holons. It is in the realm of possibility for some buses to not be in a specific FACTS-Holon.

4. Each subholon could receive the reactive support request originating from the TS and the TFD software holons, which includes the appropriate amount of variables within the subholon. Consequently, some of the subholons operate in a timely manner, which reduces operation time.

In Figure 4, the flow chart shows the holonic voltage control procedure according to the above information. There are three main points that are considered during planning of a voltage control strategy. First, although the smart interoperability can control a voltage problem, the architecture should be flexible to behave in the correct way continuously. We thus set alarm states in the voltage control progress in which the red arrow distinguishes these situations from the other steps in the flow chart. By adoption of alarm states, the TMWM software domain can manage personnel to get ready for critical conditions. Second, information about an abnormal situation must be recorded in the TAM software domain to manage future decisions about investments and other related works. Third, in the step of determining a new head of the FACTS-Holons, there is a priority list that has been initially planned. This priority list takes precedence over subholons to act as the head of the FACTS-Holons. Some priority lists are illustrated through state-machine diagrams in Figures 5a and 5b.

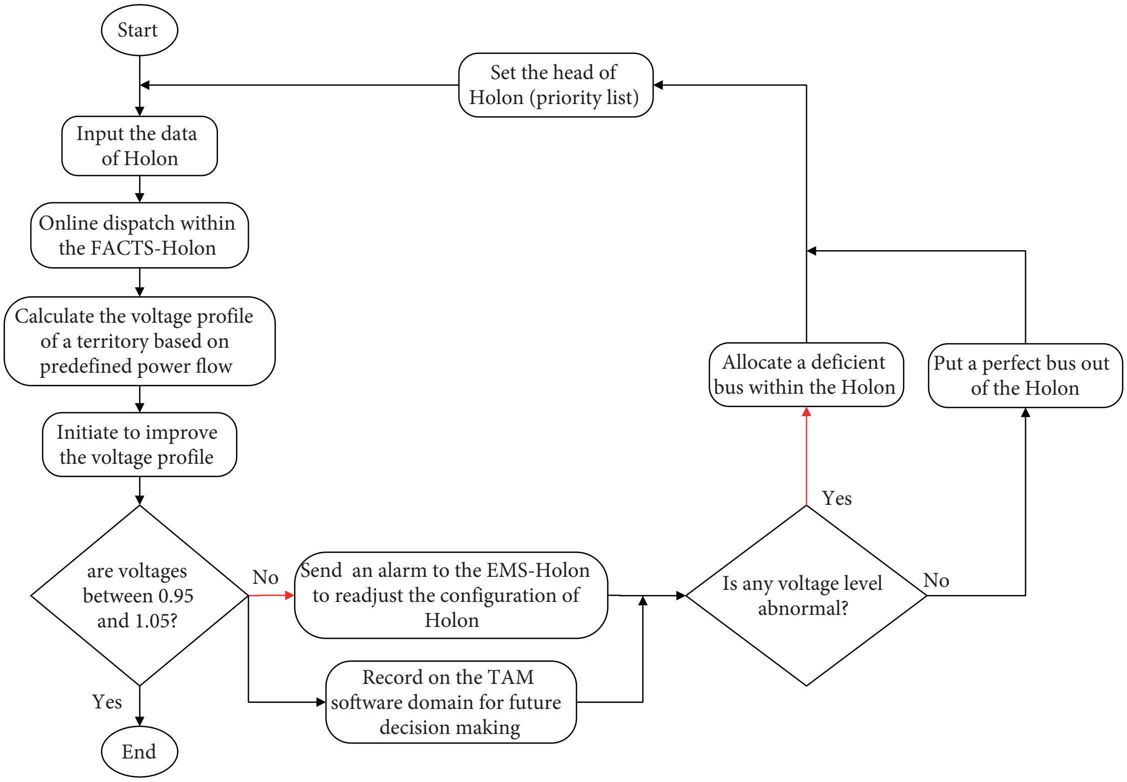

Figure 4. Proposed voltage control strategy through the holonic-based framework.

This priority is originated by the holonic feature. As shown in Figures 5a and 5b, the final state of diagrams is the TMWM software domain, which means that in this state, smart activities could not solve the problem and the operator and personnel should act immediately to break the subsystem out of the power system (i.e. isolation). The operator is responsible for choosing an effective priority list, which protects the system from outage and voltage collapse. This can be obtained from experience and recorded fault occurrences in the system. However, in this paper, we consider the priority list shown in Figure 5b for reconfiguration of holons

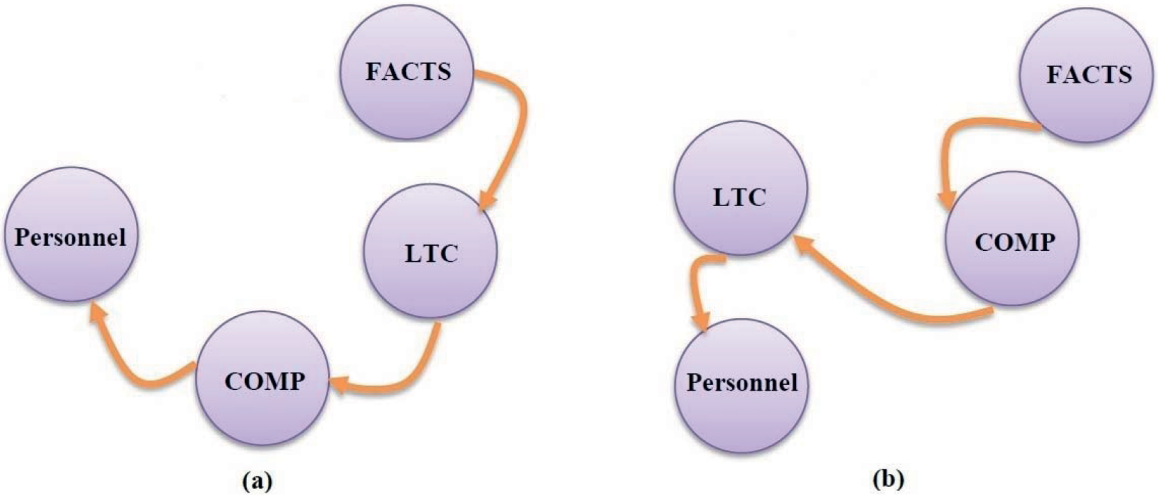

Figure 5. Priority list samples.

in the case of fault occurrence. We refer to the controller holons as the FACTS-Holon because of the beginning state of the priority diagram, which shows the FACTS-Holon as the first holon dealing with the voltage problem.

7. Case study

To assess the consequences of a holonic-based voltage control strategy, three different scenarios were considered. In the first scenario, the power system was analyzed without any control actions. In the second scenario, a transmission line outage was caused deliberately. Finally, in the third scenario, the proposed voltage control strategy was applied to the power system. There are some key notes that influence the simulation results. First, the priority list for the head of the FACTS-Holons in this study is based on the state machine diagram shown in Figure 5b. Expressly in this mode, FACTS devices have supremacy to act through a disappointing voltage level condition. Second, it is assumed that the FACTS equipment located within the FACTS-Holons is solely a thyristor-controlled series compensation (TCSC). This assumption is deliberately defined for the purpose of simplifying the problem. It means that the proposed holonic architecture is moderately flexible to comprise all of the controllers in defined zones. Third, the location of the TCSC installation is assumed as a known parameter. Finally, the simulation of proposed scenarios is applied to the IEEE-24 bus standard power system.

In this paper, the Java Agent Development Framework (JADE) is employed for simulations. This framework uses the foundation for intelligent physical agents that is codified in order to achieve coordination capability between different agents [12]. JADE has a distributed structure and provides the possibility of new agent generation and/or agent displacement as the program is running. In this framework, a proper communication platform based on agent communication language for the autonomous management of agent interactions has been prepared [12]. The agents within the holonic structure are modeled using the JADE platform, while the power system is simulated by MATLAB software. These two simulation environments are connected to each other and information is exchanged between them. For example, power system parameters such as bus voltages, active and reactive powers, etc. are sent to JADE. The agents evaluate these variables and send required commands to MATLAB to survey control alternatives.

Figure 6 illustrates the location of TCSC devices as the head of holons. The computer near the TCSC indicates that TS and TFD software domains manage all control actions through the proposed architecture. In addition, Table 1 clarifies the location of voltage controllers connected to the IEEE-24 bus standard power system. According to the previous section, in this case three possible FACTS-Holons could be created.

Let us compare the voltage levels obtained from the three predefined scenarios. It is noteworthy that an outage has occurred at the line connecting bus-3 and bus-24. Voltage profiles obtained from three predetermined scenarios are shown in Figure 7. Before the outage, all voltage levels in various nodes were within an allowable range (i.e. between 0.95 and 1.05 per unit). Once a line outage takes place, a sudden voltage drop occurs at bus-3 and bus-24. This causes initiation to operate the proposed voltage control strategy. In this case, TCSCs behave as the head of holons. As shown, this head could not ameliorate the situation. Indeed, after TCSC acted through the holonic structure, there were three buses with voltage below 0.95 per unit. Consequently, TS and TFD software domains revamped the head of the related holon based on the priority list. Now capacitors try to improve voltage conditions at bus-3 and bus-24. Figure 8 demonstrates the performance of the proposed structure to improve the voltage drop condition. By looking at the results, one can detect a powerful performance of the holonic-based voltage strategy to ameliorate the voltage profile. As can be seen in the figure, it precipitates a smooth voltage profile of around 1 per unit. This condition is obtained by adoption of head readjustment in the case of local emergency. The COMP-Holon performance causes the voltage level at bus-3 and bus-24 to reach 0.99 and 0.97 per unit, respectively.

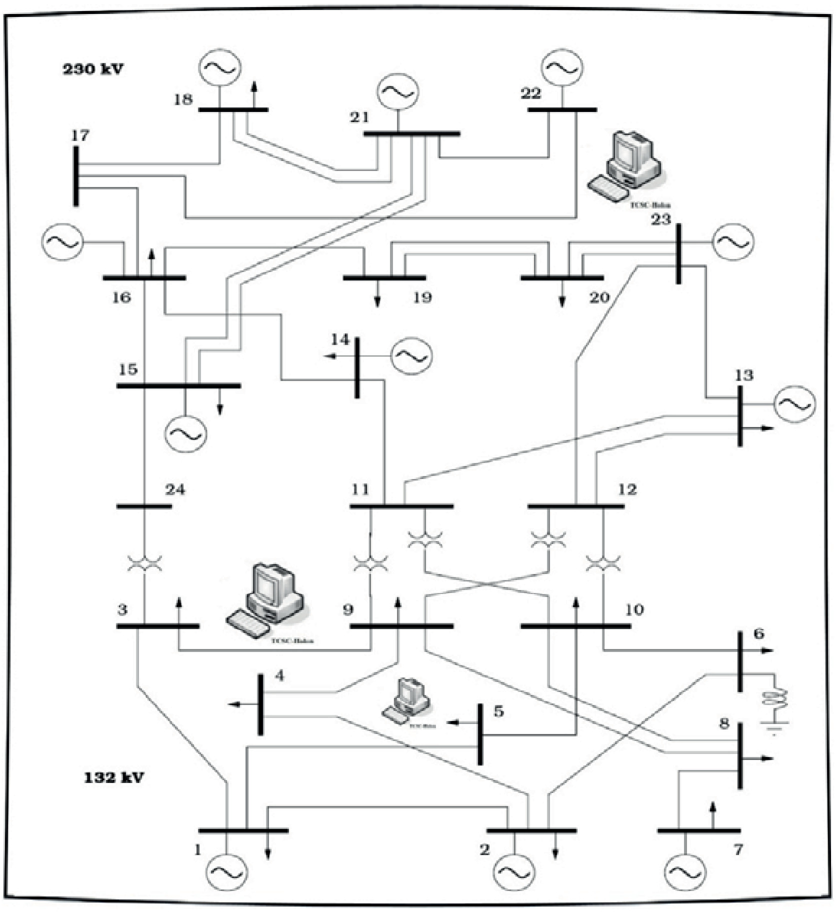

Figure 6. The IEEE-24 bus power system and TCSC locations as the head of FACTS-Holons.

Table 1. The location of voltage controllers in IEEE-24 bus standard power system.

Variables	Location	Before control action (p.u.)
TCSC1	Between 3 and 24 buses	0%
TCSC2	Between 2 and 4 buses	2%
TCSC3	Between 17 and 22 buses	5%
Capacitor1	Bus 16	0
Capacitor2	Bus 5	0
Capacitor4	Bus 11	0
Capacitor5	Bus 12	0
Capacitor6	Bus 24	0
Capacitor7	Bus 14	0
Tap1	Between 3 and 24 buses	1
Tap2	Between 9 and 11 buses	1
Tap3	Between 9 and 12 buses	1
Tap4	Between 10 and 11 buses	1
Tap5	Between 10 and 12 buses	1

Moreover, it is paramount to analyze control actions and time of processing in the proposed approach. Table 2 represents the condition of the voltage controller during corrective actions. The results in Table 2 show that there are few control actions regarding the unchanged value of elements. Also, it is remarkable that in the holonic-based strategy, the time of processing is 0.769 s, compared to 1.09 s for the centralized method. The created FACTS-Holon is represented in Figure 9. It indicates that our method puts many normal buses out of the FACTS-Holon to reduce processing time.

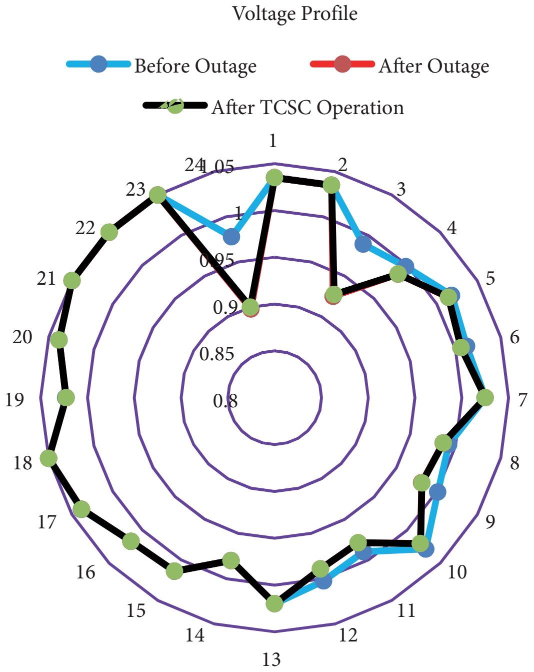

Figure 7. F-Holon performance in the proposed architecture and comparison of voltage levels in various conditions.

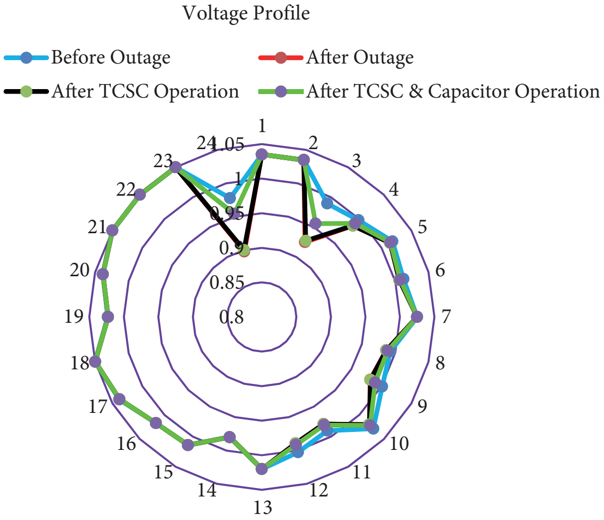

Figure 8. Comparison of three predefined scenarios and capability of COMP-Holon as the head of holon.

Table 2. Comparison of controller values before and after correction action.

Variables	Location	Before control (p.u.)	After control (p.u.)
TCSC1	Between 3 and 24 buses	0%	10%
TCSC2	Between 2 and 4 buses	2%	2%
TCSC3	Between 17 and 22 buses	5%	5%
Capacitor1	Bus 16	0	0
Capacitor2	Bus 5	0	0
Capacitor4	Bus 11	0	0
Capacitor5	Bus 12	0	0
Capacitor6	Bus 24	0	1
Capacitor7	Bus 14	0	0
Tap1	Between 3 and 24 buses	1	1
Tap2	Between 9 and 11 buses	1	1
Tap3	Between 9 and 12 buses	1	1
Tap4	Between 10 and 11 buses	1	1
Tap5	Between 10 and 12 buses	1	1

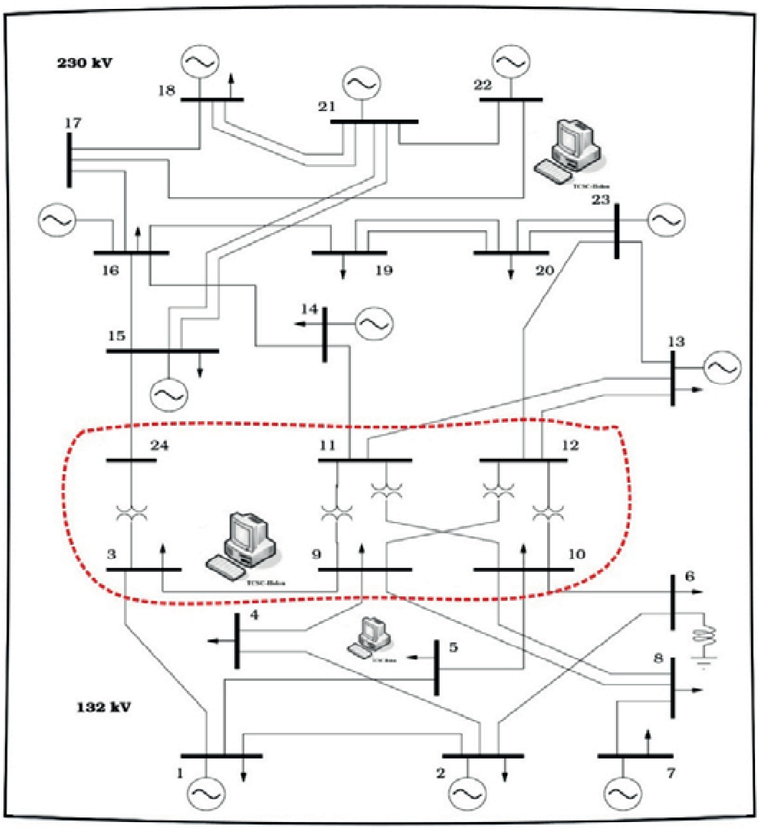

Figure 9. Configuration of FACTS-Holons created by the EMS-Holon.

In view of the active and reactive flows through the transmission lines, Figures 10 and 11 compare the condition of active and reactive power lines in the three introduced scenarios, respectively. In Figure 10, a considerable variation of reactive power flow is observed at line-27, line-24, and line-3. Also, the active power reduction is observed generally in all buses near the fault point. For example, there is a 220 MW active power reduction at line-27. In another case, the direction of active power flow is changed at line-34 and line-35 because of line outage. By comparing results, it is obvious that throughout the holonic control scheme, the reactive power flow through the lines is generally decreased. In fact, the decentralized control scheme could decrease the amount of reactive power flows through the power lines. Furthermore, our approach achieves this success with shorter processing time in comparison with the centralized scheme. In conclusion, the holonic-based voltage control strategy not only has a powerful effect on voltage profile improvement, but also has valuable influence on the active and reactive flow of lines.

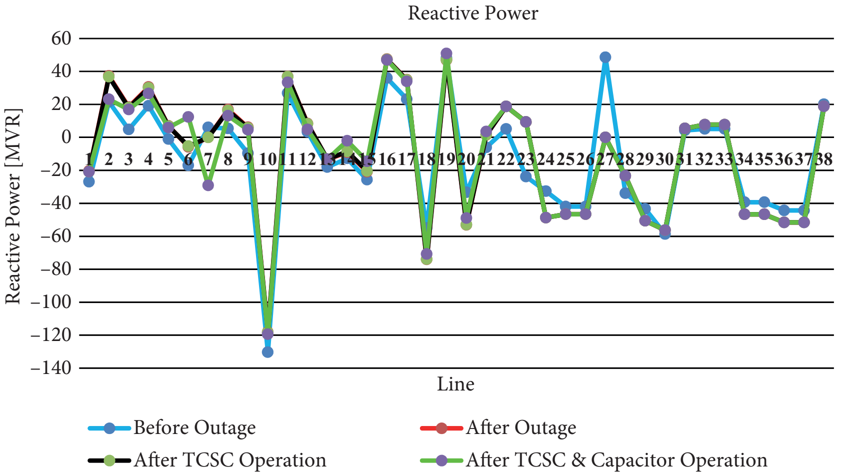

Figure 10. Reactive power improvement using the proposed architecture.

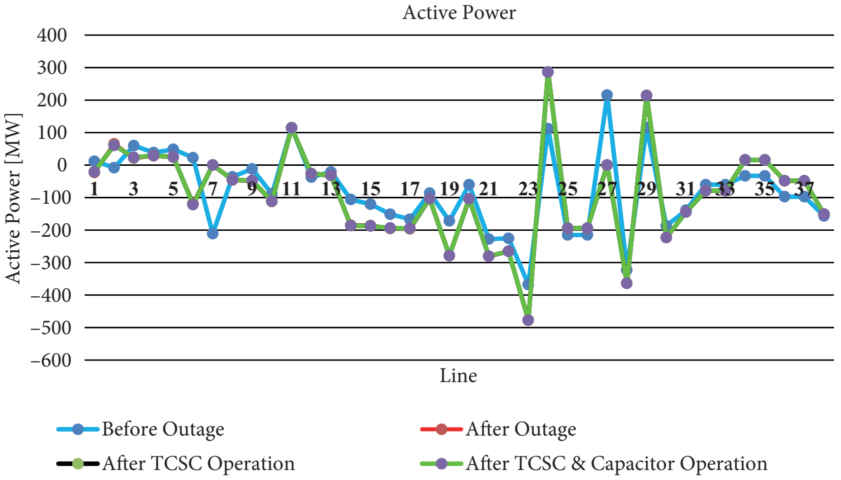

Figure 11. Active power improvement using the proposed architecture.

8. Conclusion

This paper suggests a new structural architecture to control voltage profile in collaboration with IT domains. In this paper, a voltage control process is applied locally and without any extra information exchange. To achieve this aim, first a holonic-based IT architecture was introduced. Then a hierarchical distributed framework, including two types of zones called EMS-Holon and FACTS-Holon, was proposed. Using a predefined IT model, the proposed method can deal with a minor voltage problem using a priority action list. Indeed, with the adoption of a priority list, the number of variables in each time is reduced. This can accelerate the process of control action in the case of minor problems. Moreover, a dynamic reconfiguration of the system is introduced just in the case of emergency. In fact, this approach can put the normal bus out of the holons, which allows the power flow analysis to be operated swiftly. By applying the holonic-based voltage control strategy to the power system, the processing time is reduced perceptibly. Also, corrective actions in the holonic-based scheme result in few changes in controllable variables. This result is attributed to dynamic reduction of buses located in the FACTS-Holons.

Nomenclature

PFCs	power flow constraints
x	variables vector
u	input vector
V_i	voltage of ith bus

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