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Holonic Multi-agent Control of Power Distribution Systems of the Future

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SUMMARY

A power distribution system (PDS) of the future will have homes with smart meters to monitor energy consumption, on-site grid-connected solar or wind generation, battery storage, and plug-in vehicles. The feeders will have advanced power electronic switching devices to control the system, sensors at strategic locations to measure flow of real and reactive power, voltage and current. The current level of automation in distribution systems in not adequate to handle the dynamics created due integration of a large number of these devices. In this paper, we present a Holonic Multi-agent System Architecture capable of adaptively controlling future electrical power distribution systems. The goal is to produce a general, extensible, and secure cyber architecture based on holonic multi-agent principles to support adaptive PDS. It will produce new analytical insights to quantify the impact of information delay, quality and flow on the design and analysis of the PDS. The architecture will be capable of optimizing performance and maintaining the system within operating limits during normal and minor events, such as cloud cover that reduces solar panel output. The architecture will also allow the operation of a distribution system as an island in emergencies, such as hurricanes/earthquakes, grid failures, or terrorist acts.

KEYWORDS

Power distribution systems, distributed generation, multi-agent systems, renewable resources

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1. Introduction

Advances in computer and communication technology have been continuously integrated into power systems resulting in significantly robust and reliable systems. A power distribution systems (PDS) is at the lowest end of the power systems and thus is nearest to the customers. It is estimated that capital invested in PDSs worldwide is 40% of the total investment in power systems. Of the remaining 60%, generation accounts for 40% and transmission accounts for 20%. Although PDSs are a large part of power systems, integration of cyber systems into PDS operation and control have lagged considerably behind those of generation and transmission systems. Progress on PDS automation has been relatively slow due to the significant investment needed to automate these systems with their vast number of components. As a result, most of the operation and planning of a PDS has relied on heuristics and archived information. Now with infusion of Smart Grid [1, 2] technology into PDSs, new challenges and opportunities are emerging. Federal funding of Smart Grid initiatives, which provide money to utilities to implement smart grid technologies, has accelerated activities related to distribution automation and smart metering. Similarly, the number of customers installing rooftop solar generation is increasing gradually. In the future, a high penetration of such devices will create new dynamics for which the current PDS equipment is inadequate. For example, cloud cover reduces solar power production within 10 seconds [3], which increases the flow of power from the grid causing severe voltage drop problems. Furthermore, current standards [4] do not permit operation of a PDS in islanded mode with distributed generation, although new standards are being discussed that would permit operation of a PDS as a microgrid. These new standards will be extremely valuable in maintaining customer power in the even they are disconnected from the grid such as might occur in natural disasters, such as hurricanes or earthquakes, grid failures, and terrorist acts. The complex nature of future PDSs will require them to operate as cyberphysical systems that adapt reactively and proactively under normal as well as extreme conditions.

A PDS is, by nature, highly distributed and hierarchical in structure. The requirement for reactive and proactive adaptivity across a highly distributed system naturally fits the realm of multiagent systems (MAS). The autonomous nature of agents [5] allows them to make decisions based on local knowledge and constraints thus allowing the system to adapt quickly and efficiently to its changing environment. The hierarchical nature of a PDS naturally suggests a multi-layer hierarchy such as *holonic multiagent systems* (HMAS). While MAS have recently seen significant attention in power systems, HMASs are just starting to be introduced to power distribution systems [6 - 8]. The term holonic comes from the Greek word 'holon', which is a composition of the words 'holos' (whole) and 'on' (parts). Thus, a holonic system is a system where the whole system is decomposed into parts (or agents) that are further decomposed into more agents, etc. A HMAS combines the benefits of traditional multiagent systems with holonic architecture thus yielding systems that adapt proactively and reactively both locally and globally.

There are many issues that need to be explored to operate a PDS as cyberphysical systems. A summary of these research questions are given below.

Goal-Based, Holonic Architecture – How can we define goals at each level of the architecture that are consistent between levels? How can we design organizations to support proactive and reactive adaptive functionality while incorporating security? How can we learn and use various profiles and factors to predict behavior? How should we define protocols for negotiations and information sharing?

Information Enabled Modeling - How much information is required for system state estimation and what is the cost of that information? How can the communication network adapt to provide required information for estimation, inferencing and control? How is control optimality affected by local actions? How much information uncertainty (delay, errors) can be tolerated before the system becomes unstable.

Security/Reliability – Are current protocols sufficient to ensure communications integrity? How can we detect malicious agents and reduce their potential damage? What kind of formal threat model and security assumptions are required? How can we quantify and measure risks related to agent trustworthiness?

In this paper, we provide a research framework to address these questions with the following goals.

- A general, extensible, and secure cyber architecture based on holonic multiagent principles that supports adaptive PDS behavior both proactively and reactively.
- New analytical insights to quantify the impact of information delay, quality and flow on the design and analysis of our networked holonic power distribution system control architecture.
- Novel methodology for comprehensive automation of PDSs for higher efficiency, reliability, security, and resiliency with high penetration of distributed renewable resources.

2. Power Distribution Systems

PDSs have operating voltages lower than 35 kV and feeder lengths range from 1 to 10 miles with some feeders longer than that in rural systems. Customers experience the direct impact of events occurring in a PDS because they are directly connected to it. According to some reports, 80% of the interruptions experienced by customers are due to failures in their PDS and, on average, a failure in a segment on a feeder will interrupt service to about half of the customers it serves [9]. A large part of the PDSs in the US are deployed overhead in radial configuration for both economic and technical reasons. Since underground feeders cost five to ten times more than the overhead feeders, this practice has been followed for over a century and still continues to be followed.

Although PDSs are a significant part of the power systems, very little real-time information is available to operators from the system at this level. Most of the planning and operation is based on archived information based on load research. These statistical sample data provide information for operation and planning. Generally, the only real-time PDS measurement available is from the feeder gateway at the substation. Therefore, system settings are set based on operators' experience and heuristics. Hence, most PDSs currently operate in a non-optimum mode and have difficulties in recovering from abnormal events. Attempts to automate electricity distribution to improve system operation have been ongoing since the introduction of the concept of *Distribution Automation* (DA) in the 1970s. Automation allows utilities to implement flexible control of a PDS, resulting in enhanced efficiency, reliability, and quality of electric service. Flexible control also results in more effective utilization and life-extension of the existing PDS infrastructure. Several utilities have run pilot projects and some have implemented automation based on their needs. However, there are no cases where we find a comprehensive automation of an entire PDS. In parallel with distribution automation, significant activity has taken place related to the Automated Metering Infrastructure (AMI), which deals mainly with placement of smart meters in homes to measure and monitor electricity, gas, and water consumption. Information from AMI systems can also be used by utilities for outage management.

With recent technological advancements and increased awareness of renewable energy by customers and society, the current level of automation is not sufficient. Thus, utilities are now beginning to focus on advanced distribution automation within the smart grid paradigm to make the PDS more robust and resilient. In addition, customers are becoming more willing to participate in activities that result in energy conservation and generation of electricity from renewable resources. We are currently seeing a large number of people opting to install rooftop solar generators as well as energy storage devices in their homes. Similarly, we can expect people to gradually migrate towards plug-in hybrid and electric vehicles. The result is a higher penetration of such devices in PDSs, which poses new challenges while offering new opportunities.

PDSs of the future [10] will have homes with smart meters to monitor energy consumption, on-site grid-connected solar or wind generation, battery storage, and plug-in vehicles. The feeders will have advanced power electronic switching devices to control the system, sensors at strategic locations to measure flow of real and reactive power, voltage and current. Similarly, the substation will have power electronic controls, measurements, and protection to operate the system more efficiently and reliably. The system will have a seamless communication layer from the utility's control room to customers and it will be integrated with advanced cyber systems to enable its operation. Substantially more real-time information will be available to facilitate their operation and control. We envision three different time-based modes, which are defined below. Metrics identifying key features of these modes are shown in Table 1.

Normal Mode: In this mode all the devices operate as expected and the goal is to optimize system performance to minimize losses, maximize reliability, and maximize benefits to the customers. Since the system does not see many changes under normal operation, information sampled over a longer time periods (e.g., 1 to 5 minutes) is sufficient to make control and operation decisions.

Minor Event Mode: In this mode, either a small set of devices fail or some external conditions in the system change suddenly. For example, the movements of clouds can suddenly reduce power output from rooftop solar panels simultaneously, thus stressing the system as the power deficiency must come from the grid into the PDS. Control actions and adjustments to keep system within operating limits will require faster actions over intervals of one second to one minute. The goals in this mode are to maintain balance between load, generation, and storage to maintain proper voltage in the system and to minimize interruption of power to the customers.

Major Event Mode: In this mode, a large change in system conditions takes place, such as loss of grid connection due to equipment failure, natural disasters, or terrorist acts. Current IEEE Standard 1547 [4] requires all distributed generators to disconnect from the grid upon loss of power. With new standards in place, a PDS would be able to operate as an islanded microgrid with its own resources. Unfortunately, no specific guidelines currently exist on how to maintain the balance between load and generation, to manage frequency and voltage, or to keep the distributed generators synchronized. The fact that many distributed generators have no rotating components or inertia makes the job of meeting these requirements very complex. The devices and control processes must react over intervals of one cycle to one minute. The goals in this mode are to provide electricity to customers for essential needs for as long as possible until the connection to the grid can be restored.

Table 1. Power Distribution System Modes and Metrics

Mode	Response Time	Goal	Information Granularity
Normal	1 to 5 min	Optimize performance	Coarse
Minor Event	1 sec to 1 min	Maintain operating limits	↓
Major Event	1 cycle to 1 min	Provide electricity for essential needs	Fine

3. A Goal-Based, Holonic Power Distribution Architecture

As discussed above, solving the problems associated with current PDSs require that these future systems be both proactive and reactive. It will need to be proactive to well-known changes such as consumption/production differences based on the time of day/year, weather patterns changes, and changes due to social phenomenon such as an influx of visitors. It must also be reactive to unexpected events such as the sudden loss of distribution lines or connection to the larger grid due to natural/man-made disasters or system failures. In addition, adding cyber-enabled control to a PDS causes security to become a critical issue since a cyber-enabled PDS will be a natural target for attack, either from terrorists attempting to cause widespread panic and fear or from criminals wanting to profit illegally by manipulating the system.

Our approach of using a HMAS to control a PDS is a natural fit. Intelligent agents are generally assumed to exhibit autonomy, reactivity, proactivity, and social ability [5]. Thus MAS are by nature reactive and proactive. In addition, the social ability of agents allows them to work collectively towards the common good in a variety of configurations. Finally, the autonomous nature of agents allows them to make decisions based on local knowledge and constraints thus allowing the system to adapt quickly and efficiently to its changing environment. Unfortunately, unrestrained MAS often exhibit a phenomenon known as *emergent behavior*, which can be either beneficial or harmful. One approach to harnessing the positive qualities of MAS while constraining emergent behavior is through the use of organization-based MAS [11, 12]. In an organization-based MAS, agents are assigned to play well-defined roles in the organization in order to achieve the organization's goals. Organizational *policies* constrain the behavior of the organization and techniques and metrics have been developed that can predict the overall behavior exhibited by organization-based MAS [13].

An example HMAS for a PDS is shown in Figure 1. In such a system, each agent at level *n* may actually be composed of several agents at level *n-1*, which may again be composed of agents at level *n-2*. Atomic (non-decomposed) agents may exist at any level. While similar to traditional hierarchical control systems where control passes from the top level to the lower levels, there is a major difference. Each level consists of one or more MAS that cooperate to achieve the overall system objectives. If a connection is lost between level *n-1* and level *n-2*, the MAS at level *n-2* can still operate autonomously and attempt to achieve their local goals.

Recently, work has been done on developing organization-based HMASs [11, 13]. Essentially, each MAS is designed as an organization-based MAS. In the case of a PDS, due to the regularity of the hierarchy, each MAS at the same level will in fact be the same *type* of organization, each populated with different agents based on the physical configuration of the system. As organization-based MAS cooperate towards the achievement of organizational goals, these goals become the chief control and feedback mechanism within the holonic system. For instance, at level *n*, the system may only have access to *p* kW of power and thus it would have the goal of efficiently distributing *p* kW of power. Instead of dividing *p* evenly among the agents (the sub-systems) for distribution, the agents can negotiate amongst themselves to determine exactly how best to distribute the power based on the needs of the agents (sub-systems). Thus each agent at level *n* would be assigned the goal of efficiently distributing its negotiated amount p_i of power where $p = \Sigma p_i$. Each multiagent organization will attempt to achieve its overall goal (as negotiated at the next higher level) by decomposing that goal into individual goals that are assigned to agents in the organization.

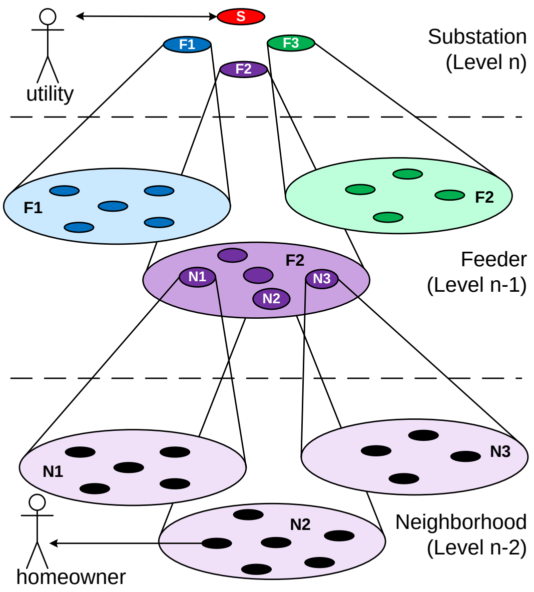

Figure 1. Holonic System

3.1. Goal-Driven Control

An abstract (centralized) representation of adaptive PDS control is shown in Figure 2, which shows a semi-traditional control loop. There are two main differences. First, the objectives of the system, specified here as goals, will change over time. These goals are a key driver of the system. The user (the utility) will specify a set of abstract goals (the Goal Specification) related to normal operation, minor event, and major event mode that are fed into the reasoning system. Second, the system uses predictions to project the future state of the system to control the system in anticipation of events. The system uses the Goal Specification, the current system state, and the predicted system state to determine the current set of goals. These goals are sent to the controller that applies controls to the system to achieve the system goals. In reality, there is a localized control loop within each multiagent organization in the system.

Within the Reasoning component, the current system state, the predicted state of the system, and the current goals are explicitly modeled and kept current. The Reasoning component updates the current goals, the current state, and the predicted state based on its goal assigned from its parent organization as well as a number of external factors such as expected load, weather, etc. Thus the system can modify its goals as the system state changes (or is predicted to change) from one state (normal operations) to another (crisis situation).

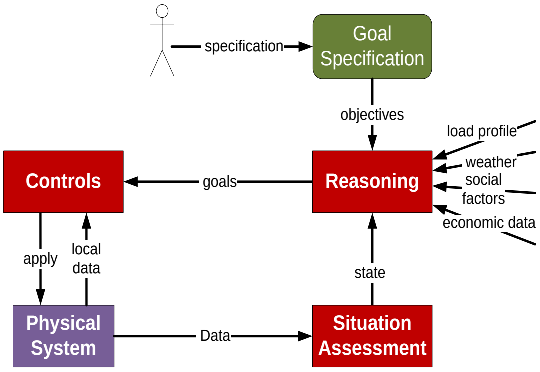

Figure 2. Cyber-physical Distribution System

4. Future Research

4.1. Goal-Based, Holonic Architecture

We propose to base our design of each organization in the HMAS on the OMACS (Organizational Model for Adaptive, Computational Systems) organizational model, which defines organizations in terms of goals, agent types, and roles [14]. In OMACS, agents (autonomous computational entities) are assigned to play roles (which capture required behaviors) in order to achieve specific goals of the organization. Each level of our proposed HMAS will consist of multiple instances of the same type of multiagent organizations. For instance, the neighborhood level will consist of several different neighborhood organizations, each specialized based on its configuration of equipment and homes. Thus, we envision designing three unique organization types in the architecture, one each for the substation, feeder, and neighborhood level.

4.2. Information Enabled Modeling

The success of an HMAS-controlled PDS hinges on a robust and reliable information network that overlays the physical network. Information exchange between levels of the HMAS and amongst agents within a level enables effective control and management of the physical system. For example, the actions taken by an agent typically depends on many factors including, (1) overall goal and the specific goals assigned to an agent; (2) measured data regarding the power system; (2) extrinsic complete or incomplete knowledge of the global state of the power system; (3) information shared from other agents regarding their actions, and (4) human factors. Much of the information required to act is extraneous information that is shared via a communication network. Communication links among agents introduce a new level of uncertainty (in terms of delay, accuracy and usefulness) in the operation and control of the overall system. This is one of the fundamental challenges in any cyber physical system and our HMAS-controlled PDS is no exception. Furthermore, in case of a major fault requiring quick action, it is unreasonable to assume knowledge of complete system information and control actions are typically based on partial information. We propose to develop new analytical insights to quantify the impact of information delay, quality and flow on the design and analysis of our networked holonic power distribution system control architecture.

4.3. Security/Reliability

The flexibility provided by an HMAS increases the system's resilience to failures, but also opens up more attack vectors to malicious users. The problems associated with security of the communication infrastructures include malicious agents, measuring and gauging the threat levels, and run-time monitoring and detection of malicious agents will be addressed.

5. Conclusions

In this paper, we have addressed issues related to operation and control of distribution systems of the future with high penetration of distributed renewal resources. A framework based on holonic multi-agent architecture has been proposed for control of distribution system. Topics for future research to accomplish goals described in this paper are identified.

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