Next-Generation Monitoring, Analysis, and Control for the Future Smart Control Center

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***Abstract*—This paper proposes a vision of next-generation monitoring, analysis, and control functions for tomorrow's smart power system control centers. The paper first reviews the present control center technology and then presents the vision of the next-generation monitoring, analysis, and control functions. The paper also identifies the technology and infrastructure gaps that must be filled, and develops a roadmap to realize the proposed vision. This smart control center vision is expected to be a critical part of the future smart transmission grid.**

***Index Terms*—Power system control, power system monitoring, power system operation, smart control center, smart grid.**

I. Introduction

POWER SYSTEM operators need to operate the transmission system under increasingly complex conditions. The formulations of power markets and open access policies have introduced a variety of challenges in system operations. Renewable generation, energy storage, demand response, and electric vehicles introduce further complexity to system operation. The current monitoring, analysis, and control technology for transmission networks may not be able to meet these increasingly diverse future challenges. Looking ahead, we can see that enhancing the functionalities of system operation will be necessary to maintain and improve power system reliability and power quality.

Energy research organizations have made considerable progress in formulating and promoting a vision for of the future smart power grids [1]–[16].

The IntelliGridSM program, initiated by the Electric Power Research Institute (EPRI), is creating the technical foundation for a smart power grid that links electricity with communications and computer control to achieve tremendous gains in reliability, capacity, and customer services [4], [5]. This program provides methodologies, tools and recommendations for open standards and requirement-based technologies with the implementation of advanced metering, distribution automation, demand response, and wide-area measurements. A key program goal is to enable interoperability among advanced technologies of the the power system.

The SmartGrids program, set up by the European Technology Platform (ETP) in 2005, created a joint vision for the European networks for the year 2020 and beyond [6], [7]. The objective features identified for Europe's electricity networks are flexibility to customers' requests, accessibility to network users and renewable power sources, reliability for security and quality of power supply, and economics to provide the best value and the most efficient energy management.

A Smart Grid Task Force was established by the U.S. Department of Energy (DoE) under Title XIII of the Energy Independence and Security Act of 2007. In its Grid 2030 vision, the objective is to construct the 21st-century electric system to provide abundant, affordable, clean, efficient, and reliable electric power anytime, anywhere [1]. The expected achievements through smart grid development will not merely enhance reliability, efficiency, and security of the nation's electric grid, but contribute to the climate change strategic goal of reducing carbon emissions.

There are also noteworthy research and development activities underway in both the industry and academia [8]–[16]. References [8] and [9] present smart grids for future power delivery. Reference [10] discusses the integration issue in the smart grid. Reference [11] presents interesting and promising concepts such as energy internet. Specific technologies such as smart metering infrastructure were presented in [12].

A majority of above activities focus on distribution and demand-side systems, while little focus is placed on transmission grids.

Emerging technologies, such as the synchrophasor technology, open up opportunities to improve monitoring, analysis, and control functions. In the last few years, several countries have installed phasor monitoring units (PMUs) on their electrical systems. The following countries are reported to have installed and integrated PMU for research or are developing prototypes [17]–[28]: Brazil [17], Baltic [18], China [19], [20], France [21], Japan [22], Korea [23], Mexico [24], Norway [25], Scandinavia [26], and the United States [27], [28]. Most of the applications implemented can be categorized into the following areas.

- *Monitoring*: Visualization solutions improving operator displays and allowing detection of instabilities [29]–[36].
- *Analysis*: event analysis, reliability awareness, and assessment [37]–[42].
- *Control*: stability control, fault location, and adaptive relaying [43]–[54].

There is a critical need to develop a clear vision of the power system operation of the future. Given that vision, we can create

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the alignment necessary to inspire passion, investment, and progress toward an advanced grid for the 21st century. To achieve the vision, we need a roadmap to integrate technologies, to break down the barriers, and to develop and deploy the necessary technologies. Reference [60] is a recent effort in developing future smart transmission systems, including the overall framework and three components in the framework, namely substations, control centers, and transmission networks. This paper, as a companion of [60], discusses details related to the present status of the control centers and a vision and roadmap towards the future smart control centers.

In this paper, the present technologies of monitoring, assessment, and control in power system control centers are briefly reviewed in Section II. Then the main characteristics of the future smart transmission grid and the vision of the future monitoring, assessment and control functions are described in Section III. The discussion compares the vision with the present technology and identifies the technology and infrastructure gaps that must be filled to fully implement the future vision. Next, the paper presents a roadmap towards the prospective monitoring, assessment and control technologies in future control centers in Section IV. The conclusions are presented in Section V.

II. Review of Present Technologies

There are three main functions in power system operation: monitoring, analysis, and control. If we use human system operators as a metaphor, the monitoring functions are the operators' eyes, the analysis functions are the operators' brains, and the control functions are the operators' hands.

The present power system operation, especially monitoring, analysis, and control functions, were initially developed in the 1960s. The technologies invented at that time have led to computerized one-line diagram visualization, state estimation, and contingency analysis. The typical present technology of monitoring, analysis, and control is briefly summarized here.

- The monitoring system is based on raw data or output from state estimation, which is subject to a considerable delay at the scale of tens of seconds to minutes. It is usually based on the local information of a control area. Interaction with neighboring systems is limited. Computer-aided visualizations are available, but only in one-line diagrams without customization.
- The security assessment is based on contingency screening, which is essentially a steady-state power flow analysis. Voltage stability analysis is simulation-based, which depends on the accuracy of the models and the performance of the state estimator.
- The protection and control system is mostly based on local information. Some recent work considering global impact using special protection schemes (SPS) is based on offline studies to adjust control strategies. In general, the coordination of different protection and control systems is limited. The process of system restoration is mainly based upon operators' experience and results from offline studies.

As shown in Fig. 1, the current system operation at control centers is reactive. Operators' eyes are reading the raw data, with limited information provided to the brains. The brains are trying to comprehend the current situation, generally based on past experience and preliminary assumptions. Such limited functionality may not be adequate to meet the needs of an increasingly complex and stressed power grid.

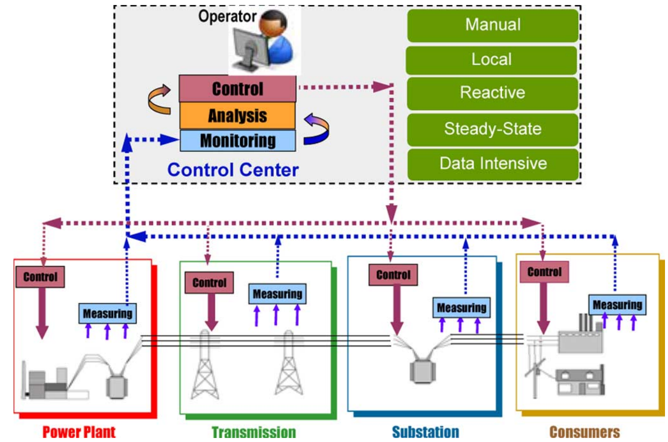

Fig. 1. Current control center and its functions.

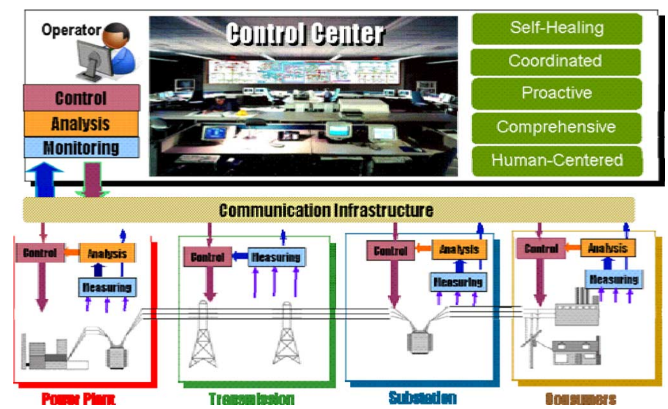

Fig. 2. Future control center and its infrastructure and functions.

The growth of new energy resources, the emerging transmission and substation technologies, and advances in communication and computing infrastructures [55]–[59] require power system engineers to re-think how to perform real-time monitoring, analysis, and control.

III. Vision of Next-Generation Monitoring, Assessment and Control for Future Control Centers

We propose a vision to design and develop the next-generation monitoring, analysis, and control technologies to move the industry towards a smarter transmission grid.

As shown in Fig. 2, the vision for future control centers, also referred to as smart control centers, can be a critical part of the overall framework of the future smart grid. This vision has the following five key characteristics:

- human-centered;
- comprehensive;
- proactive;
- coordinated;
- self-healing.

A. Human-Centered Online Monitoring

Human-centered is the key characteristic of the next-generation monitoring functions in the future smart control centers. In this context, human-centered has two meanings: information-directed and customized.

1) From Data-Intensive to Information-Directed: The next-generation monitoring functions shall provide operators useful information rather than raw data. With more and more deployment of monitoring devices (e.g., equipment health sensors and PMUs), we now have more data available to help system operators monitor the power system condition in real time. However, more data does not necessarily mean more information. We need to transform the huge volume of data into useful information. It is the operators' responsibility to define what information is needed.

For example, the protection system at substations can record disturbance events. Rather than providing system operators with the entire volume of recorded data, information on specific types of faults can be provided to system operators. Providing such information would save a great amount of time for operators. This information can be further utilized in dynamic security assessment to help system operators analyze system stability issues and develop optimal remedial strategies.

As more and more sensors are deployed at substations and transmission lines, the sensor data can be analyzed for online determination of equipment health rather than sending the sensor data to system operators. Providing system operators with the potential component failure information can help them foresee the system problem and develop a proactive mitigation plan.

2) From Limited Customization to More Flexibility: Since the information is presented to system operators who are human beings, the monitoring functions shall employ advanced visualization techniques with the goal of helping each operator to digest information quickly.

We need to recognize that each operator is unique and has his/her own preference for digesting the information. The present monitoring technology in control centers adopts standard human–machine interface and does not offer much flexibility for customization. The next-generation monitoring functions shall offer customization capabilities so that individual operators can easily configure the human–machine interface based on their visualization preference. With the application of the customized monitoring functions, system operators will be more effective in understanding the current operating conditions, identifying abnormal operating conditions, foreseeing potential problems in the near future, and so on.

In summary, the human-centered monitoring functions can help system operators improve real-time situational awareness.

B. Comprehensive and Proactive Online Analysis

Comprehensive and proactive are the two key characteristics of the next-generation online analysis functions. In this context, comprehensive has a twofold meaning.

i) The next-generation online analysis functions shall help system operators determine "comprehensive" operating boundaries in real time. Comprehensive operating boundaries include both thermal limits and stability (voltage stability and transient stability) limits.

ii) The next-generation online analysis functions shall apply a "comprehensive" approach to help system operators determine the operating boundaries. "Comprehensive approach" means combination of a simulation-based approach and a measurement-based approach.

1) Combine Steady-State Security Assessment With Dynamic Security Assessment: At present, online analysis at control centers typically performs steady-state contingency analysis. Each credible contingency event is analyzed using power flow studies. The thermal and voltage violations are then identified.

The future control centers shall carry out both steady-state and dynamic security assessment in real time to help system operators determine the comprehensive operating boundaries. The comprehensive operating boundaries include thermal limits, voltage stability limits, small-signal stability limits, and transient stability limits.

2) Combine Simulation-Based Analysis With Measurement-Based Analysis: The next-generation online analysis functions shall apply a comprehensive set of approaches to help system operators calculate the operating boundaries. A comprehensive set of approaches includes both simulation-based approaches and measurement-based approaches.

The accuracy of simulation-based analysis fully depends on the accuracy of modeling the generation, load, and transmission facilities. Uncertainties in these factors can reduce the accuracy of results of simulation-based approach. Inaccurate results may lead operators to make incorrect decisions. Moreover, the simulation-based approach also relies on the state estimator to provide steady-state solution for further analysis. In extreme operating conditions when the state estimator fails to converge, the simulation-based approach also fails to help operators develop the mitigation plans to handle the problems.

The wide implementation of disturbance monitoring technologies, such as PMUs, opens the door to new opportunities for measurement-based analysis. The measurement-based analysis uses the measurement data at substations to calculate the stability margin in real time.

The simulation-based approach and measurement-based approach are complementary to each other. The results obtained from the measurement-based approach can validate the models used in the simulation-based approach. The simulation-based approach can study what-if scenarios and develop preventative control strategies. The stability margin calculated using the measurement-based approach can trigger the automatic control based on the preventive control strategies produced by the simulation-based approach.

3) From Reactive Analysis to Proactive Analysis: The present online analysis is based on the current operating condition. This does not consider future system conditions. In the future, online analysis shall take a proactive approach to perform look-ahead simulation on the future system conditions.

The integration of renewable energy sources will introduce more uncertainties into the power system. With the ability to foresee potential problems, the next-generation proactive online analysis will optimize resources (such as demand response and energy storage) in order to improve reliability and achieve economic operation.

By enabling sufficient foresight, the next-generation analysis functions allow system operators to take a proactive approach to develop optimal control strategies and mitigation plans.

In summary, the comprehensive and proactive analysis functions can help system operators improve online analytical capabilities.

C. Coordinated and Self-Healing System Control

Coordinated and self-healing are the two key characteristics of the next-generation control functions.

1) From Isolated Protection and Control Strategy to Coordinated Protection and Control Strategy: Traditionally, each control scheme is designed to solve a particular problem. The parameters were developed based on offline simulations and largely remain fixed. There is a lack of coordination among protection and control systems. As modern power systems have become more interconnected with increasing stress levels, each disturbance may cause multiple protection and control schemes to respond. There may exist negative interactions that can worsen system conditions, which present challenges and risks in system operation.

When a power system experiences a disturbance, the next-generation coordinated protection and control systems will perform according to the optimal control strategies developed by online security assessment and shall quickly bring the system to a stable operating condition with minimum control efforts.

2) From Offline-Based Restoration Strategy to Online Restoration Plans: The current restoration plans are developed through offline studies, based on assumptions regarding likely scenarios… However, the restoration strategy developed from such studies may not work well following a blackout because the real operational situation may vary from the assumed scenarios.

When part or all of the power system is blacked out, the next-generation self-healing control scheme shall effectively restore the system and bring it back to a normal operating condition.

In summary, the coordinated and self-healing control functions can help system operators improve control capabilities.

By achieving the above capabilities, we can streamline the monitoring, analysis, and control functions, and implement an integrated and automated control center.

IV. Technology Roadmap to Achieve the Vision

The previous section provides the vision of the future real-time monitoring, analysis, and control systems. To implement the vision, critical technologies need to be developed and deployed. In this section, the technology roadmap to achieve the next-generation monitoring, analysis, and control towards smart transmission grid is developed.

A. Critical Technologies

Critical technologies needed to achieve the next-generation human-centered monitoring system, the next-generation comprehensive and proactive online analysis functions, and the next-generation coordinated and self-healing control functions are described in Tables I–III.

TABLE I
Technologies to Achieve the Next-Generation Human-Centered Monitoring System.

	Critical Technology
1	**Geographic Information System (GIS) for Transmission System**
	The present energy management system (EMS) uses one-line diagrams to display the power system configuration. However, it does not provide the geographic location information. The GIS shall be implemented at the transmission level in order to help system operators monitor the wide area system condition, quickly identify the fault location and coordinate with the fleld team to clear the faults. Given the fact that the GIS has been implemented at the distribution level, we envision that it may take 3-5 years to implement GIS at the transmission level.
2	**Advanced Visualization with Customization Capabilities**
	Advanced visualization techniques need to be developed so system operators can quickly digest the information. The advanced visualization techniques shall also allow system operators to customize the GUI display based on individual preferences. In recent years, a lot of research and development efforts have been devoted to advanced visualization techniques. A number of commercial visualization software packages have been developed. Further research is still needed to investigate how human factors affect system operators' capabilities of digesting the information. A customization module needs to be developed in the visualization package. Based on the current status, the implementation of advanced visualization with customization capabilities requires at least 5-7 years.
3	**Advanced Alarm Management**
	The current alarm management system uses technology developed in the late 60s. In normal condition, there are no alarm messages. During disturbances, existing alarm management methods are not effective and become overloaded with useless information. Normally, the number of alarms is so large that it is impossible for system operators to analyze the situation in time. This often means that it is not known until long afterwards where or how a disturbance is originated. The advanced alarm management shall track ongoing root causes and present only the information critical to grid operators. This can help operators understand the current and developing abnormal operating condition and increase their situational awareness, enabling them to avoid large blackouts by allowing them quick action in short time period during which the problems escalate. The implementation of advanced alarm management may take 8-10 years.
4	**State Measurement**
	The present monitoring system in a control center depends on state estimation. With the implementation of sufficient synchrophasor measurements, state measurement will eventually replace the current state estimation. The state measurement will be more efficient and robust than the present state estimation. State measurement is the foundation to enable real-time stability assessment. To accomplish state measurement, the transmission system needs to install adequate number of synchrophasor measurements and set up the communication infrastructure, which may take about 10 to 15 years. Recently, relay manufacturers released new products equipped with synchrophasor capabilities. This may accelerate transferring from state estimation to state measurement.

B. Technology Roadmap

In the near term, we envision that the monitoring system shall implement the geographic information management such that the operators will not be overwhelmed by messages, which can

TABLE II
TECHNOLOGIES TO ACHIEVE THE NEXT-GENERATION COMPREHENSIVE AND PROACTIVE ONLINE ANALYSIS FUNCTIONS.

	Critical Technology
1	**Online Dynamic Security Analysis**
	At present, online analysis at control centers typically performs steady-state contingency analysis. Each credible contingency event is analyzed using power flow studies. The thermal and voltage violations are then identified. The future control centers shall carry out both steady-state and dynamic security assessment in real time to help system operators determine the comprehensive operating boundaries. The comprehensive operating boundaries include thermal limits, voltage stability limits, small-signal stability limits, and transient stability limits. The implementation of online dynamic security assessment will take about 3-4 years.
2	**Measurement-based Stability Analysis**
	The present analysis is based on simulation results using pre-defined models. The broad implementation of disturbance-monitoring technologies, such as PMUs, opens new opportunities for measurement-based analysis. The analysis functions shall take both simulation-based and measurement-based approaches, as they are complementary to each other. The results obtained from the measurement-based approach can validate the models used in the simulation-based approach. The simulation-based approach can study what-if scenarios and develop preventative control strategies. Based on current status, the implementation of an integrated simulation-based approach and measurement-based approach will need 5-7 years.
3	**Proactive Analysis**
	The present online analysis is based on the current operating condition. This does not consider the future system conditions. In the future, online analysis shall take a proactive approach to perform look-ahead simulation on the future system conditions. By enabling sufficient foresight, the next-generation analysis functions can optimize resources (such as demand response and energy storage) in order to improve reliability and achieve economic operation, allowing system operators to take a proactive approach in developing optimal control strategies and mitigation plans. The implementation of this look-ahead proactive analysis will take 8-10 years.
4	**Probabilistic Risk Analysis**
	The present technology applies N-1 contingency in a deterministic approach. In the future control centers, N-x or cascading failure should be considered with probabilistic risk analysis. When the system is most stressed, the higher order contingency and possible cascading failures after an initial contingency event are more likely to happen than before. Since the dimension of complexity grows drastically with higher order contingencies, it is necessary to consider the probability of occurrence and the impact of contingency. Therefore, a probabilistic approach is desired. Given that some pilot research work has started in investigating probabilistic risk, we envision that it will take 2-3 years to accomplish the component conditional probabilistic risk analysis, and 10 years or more on N-x or cascading failure analysis.

literally block the operators from performing meaningful corrective actions. Also, a comprehensive online dynamic security analysis should be implemented such that true real-time security signals will be displayed. This is very important since the voltage magnitude is not a good indicator of voltage stability. As previously mentioned, true stability margin assessment in terms of voltage stability as well as transient stability and oscillatory stability must be evaluated. In addition, automatic voltage control is expected to be implemented. This is because voltage stability is an increasing concern in the U.S. power system and the trend of the time to voltage collapse tends to be decreasing.

TABLE III
TECHNOLOGIES TO ACHIEVE THE NEXT GENERATION COORDINATED AND SELF-HEALING CONTROL FUNCTIONS.

	Critical Technology
1	**On-line Interactive Restoration Tool**
	The current restoration plans are developed offline by system planners based on certain assumptions on likely scenarios.. However, the offline developed restoration strategy may not work well in real time right after the blackout because the real operational situation may vary from the presumptive ones. System operators need an online interactive system tool to assess the restoration strategies in real-time based on the current system condition. The online interactive restoration tool shall provide suggested restoration plan and recommended restoration procedures. When part or all of the power system is blacked out, the online interactive restoration tool can help effectively restore the system and bring it back to a normal operating condition within a minimum amount of time. It will take 5-7 years to implement such an online automatic restoration decision tool.
2	**Coordinated Protection and Control System**
	The present technology in power system protection and control has been considered unsatisfactory to provide a robust, fast, and efficient support to system-wide disturbance. The present protection and control systems are designed individually. Each of them aims at solving a single problem. There is lack of system-wide coordination among those protection and control systems. This sometimes can worsen the system conditions during an emergency. The latest developments in communication, control and computing technologies open new opportunities to enable coordinated protection and control systems. The future protection and control systems should be able to fully utilize the real-time, system-wide information, dynamically adjust the protection and control to achieve optimal control performance with minimum control efforts. The implementation of the coordinated protection and control requires enhancing the existing computing and communication infrastructures, therefore it will take 8-10 years.

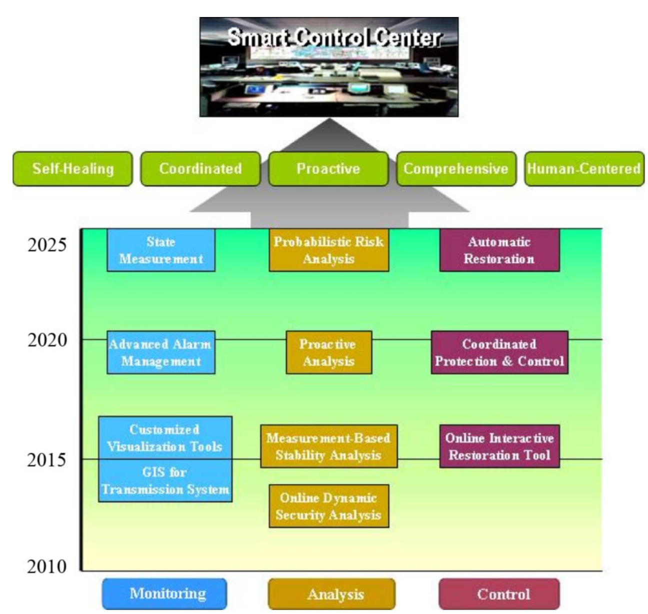

Fig. 3. Technology roadmap towards the future smart control centers.

In the midterm the future system shall be equipped with the capability to monitor wide-area frequency and voltage stability. This requires communication protocol standardization. Also, security assessment should be combined with cost or impact such that a risk evaluation will be implemented. In the control part, a coordinated protection and control shall be implemented to replace the present SPS.

In the long term the monitoring system should have the advanced alarm management capability. The assessment function should perform proactive analysis such that the system will be well prepared for potential disturbances. A coordinated protection and control system should be implemented.

We envision that by 2025 the next-generation monitoring, analysis, and control center will be able to identify the fault location and type because of the large penetration of PMU-based state measurement. Probabilistic risk assessment for N-x contingencies will be performed. And automatic protection and restoration will be achieved. Fig. 3 illustrates the technology roadmap discussed above.

V. Conclusions

This paper presents a unique vision of the next-generation monitoring, analysis, and control functions to achieve a smart control center. It aims at promoting technology innovation to achieve a reliable, economical, and sustainable delivery of electricity. The five key characteristics of the future smart control center have been described in detail. In this paper, the present status to the future vision are discussed, the critical technology gaps are identified, and the technology roadmap to reach the proposed vision are proposed.

The existing communication and computation infrastructures also need to be enhanced to support the implementation of the next-generation monitoring, analysis, and control functions. The present communication infrastructure is a mix of telephone lines, broadband over power lines, wireless communication, microwave, optical fiber, etc. To implement the vision of the smart control center, the communication infrastructure needs to be upgraded to a fast, dedicated communication system with standard protocol and quality of service.

The present computing technology in most control centers is based on sequential computing. To support the next-generation monitoring, analysis, and control functions, the parallel computing infrastructure need to be implemented with proper prioritizing and scheduling different real-time simulation tasks.

Government agents, utility executives, energy policy makers, and technology providers must agree on a common vision and take actions to accelerate the process towards final deployment. Given the scale of the effort required and the enormity of the challenges ahead, collaboration among different sectors is essential and should be developed through various channels in order to ensure and accelerate the success of the future smart control centers.

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