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Distribution Automation Technology and Applications in Smart Grids

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Abstract. The global Energy transition is hitting traditional grids. There are also more distributed power and varied users' demands Distribution Automation (DA) is the core technology for distribution grid to solve such problems. DA is a hierarchical "master station - substation - terminal" structure. And it makes the grid have more observability, controllability, self-healing ability, and operational ability by using such as supervisory control and data acquisition (SCADA) and fault location isolation service restoration (FLISR). This paper conducts a detailed review of the main characteristics and requirements of smart distribution networks. And give an in-depth analysis about distribution automation system,which include hierarchy,communication technologies ,application like state estimation ,fault self-healing ,voltage optimization. Finally, the paper mentions engineering cases for the demonstration of the actual application. It talks about projects such as EU ERI Grid and Tsinghua microgrid platform. This paper has also identified some currently existing major problems such as insufficient system design, regional development imbalances, technological stagnation, and insufficient professional talent. As for solving these problems, this paper puts forward solutions such as establishing a unified information platform, integrating Internet technology, strengthening infrastructure, and training. The research results show that distribution automation technology greatly improves power supply reliability with less time, making it an important reference for realizing "dual carbon" goals and building an Energy Internet. Looking forward, the technology is expected to evolve towards digital twins, AI-driven adaptive control, and multi-energy coordination.

Keywords: Smart Grid, Distribution Automation, Self-healing Control, Fault Location, Optimal Operation

1. Introduction

Nowadays, the world energy structure is quickly changing to more clean and low-carbon type. The old-style power grid using human workers meets difficulties because many small energy sources join in and customers want more different kinds of electricity services. These issues result in slow fault response, inadequate power supply reliability, and low resource allocation efficiency, making it difficult to meet the construction requirements of new power systems. Meanwhile, the rapid advancement of network technology has facilitated the widespread promotion of intelligent

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equipment. By using distribution automation technology, the smart grid can see and control the distribution network because it has advanced sensing, communication, control and information technology. It has become the main way to solve the problem between energy supply and demand, also can improve power grid safety and service quality, which is very important for keeping energy security, pushing the 'dual carbon' goal, and building the energy internet [1].

This paper begins by establishing the foundational attributes of modern smart distribution networks, identifying them as systems capable of autonomous recovery (self-healing), bidirectional communication (interactivity), and comprehensive observability (visualization). It describes the system's classical three-tier structure, consisting of main control center (master station), intermediate substations, and RTU remote terminals unit. It can also do some important things like getting real-time data and fixing problems by itself.

A number of existing studies focus on how to improve some part, e.g., how to improve fault localization algorithm. But this narrow view usually misses the bigger picture like each platform not sharing all its data together ("info silo"), or some tech not working well with other tools. But instead of this, this study accounts for the whole technical integration right till the end of the distribution automation framework. This is through linking theory research in technologies with real world usage in the field.

The study methodology combines a comprehensive literature review, a functional decomposition of the technology, and an analysis of real-world case studies. This approach effectively clarifies the system's architecture and maps key technologies to specific application scenarios. Furthermore, the paper proposes targeted strategies to resolve existing problems.

2. Core concepts: smart distribution network and distribution automation

2.1. Characteristics and requirements of smart distribution network

In the era of digitization, the concept of a smart electric grid is tuned with a few improvements that describe the hierarchy of a distributed network which includes smart transformers, transmission lines, distributed substations with other electric accessories such as smart meters, etc. However, to automate the ecosystem between industrial manufacturing units towards the consumer. The smart grid performs a vital role that consists of a digital system, operational controls, automation, and computing resources which make the system perform two-way communication between the provider and consumers. As compared to the previous systems, the energy power suppliers are the only person that knows the failure of power and related fluctuation faced by the consumers, and it will be resolved when users call. Whereas the smart grid technology responds directly while automatically receiving data of power failure. The role of the service provider is crucial; however, it manages request for electric supply fails and provide auto-respond to the affected areas because of the wireless sensor network capability, and the components of the smart grid provide real-time data. It collects data from the power generators, transformers distributed networks, transmission load, and then the smart meters that are placed on the end-user side. According to the port of the American Agency of Sustainable Energy, the use of renewable energy is increasingly growing day-to-day, where the role of the smart grid is remarkable, while energy generation is to manage load and distribution. There are a few working operations/objectives of smart grid technology discussed as follows, which make the ecosystem efficient and reliable.

The intelligent distribution network is a key component of the smart grid and the direction of development for distribution systems. It is based on a flexible, reliable, and efficient network structure and a highly reliable and secure communication network. It deeply integrates advanced

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computer technology, information and communication technology, advanced sensing and measurement control technology, automatic control, and artificial intelligence on top of the traditional distribution network. By deploying intelligent equipment such as smart meters and distribution automation terminals on a large scale, it constructs a perception network covering all aspects of the distribution network, and collects and analyzes massive amounts of real-time operational data. At the same time, the introduction of advanced strategies and algorithms such as hierarchical distributed coordinated control and multi-objective dynamic optimization can quickly calculate the optimal network topology and power flow distribution based on the real-time state of the distribution network and load forecasting results. With the help of the distribution automation system, closed-loop control can be achieved, ultimately meeting the future distribution system's needs for user interaction, high-quality power supply, high-penetration distributed generation access, as well as fault self-healing, global optimal operation, and other aspects, becoming a modern distribution system with "observable, controllable, dispatchable, and self-healing" capabilities [2].

2.2. What is Distribution Automation System and how it works

The Distribution Automation System (DAS), shown in Figure 1, is a complete automation system built on computer, communication, and control technology, along with power system theory. It enables real-time monitoring, remote control, intelligent analysis, and operational optimization of the distribution network. The system can work on its own or integrate with SCADA, PMS, and GIS systems, creating a full "sense-decide-act" cycle. The DAS is built on a hierarchical framework consisting of three main layers, which are linked by a dedicated communication network. The master station is the "decision center" that collects data and makes smart decisions. Substations form “regional hubs” of local data processing and control. Finally, distribution terminals like FTUs and TTUs are the “perceptions endpoints” for picking up information. The communication network combines optical fiber, wireless and power line carriers so as to ensure reliable and quick information transmission [3]. By cooperation among different levels, the system achieves three functions: firstly it is capable of monitoring and remote control in real time, making the distribution network visible and controllable, Secondly, quick fault handling, greatly reducing power outage times to improve supply reliability Thirdly, optimized operation and smart management, using multi-source data to do advanced jobs like load prediction and reactive power optimization, helping change the distribution network from 'experience-based' to 'data-based', thus raising overall efficiency and lean management level.

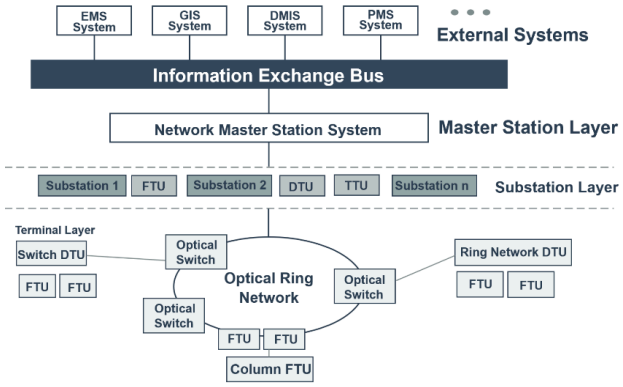

Figure 1. Schematic diagram of Distribution Automation System

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3. Distribution Automation System architecture and technical components

3.1. System layered architecture (master station, substation, terminal)

DAS architectural design is a basic decision that greatly affects its technology, economics, and operations. A big picture/systems level view is needed. On the majority of them is used a hierarchical, multi-tier structure. And the peak of the pyramid would be the Master Station, this could be located in a main centralized control center, and it would be responsible for supervising and monitoring the entire distribution network. It accomplishes global tasks like optimal power flow, fault management, load distribution, etc., by getting and analyzing real-time data to preserve network stability and efficiency. Substation layer intermediate tier can be seen as a regional data concentration and control gate. It aggregates data from all the many terminal devices under its authority, reports the information to the Master Station, and broadcasts control commands down. This necessary layer can be scalable or maybe eliminated if it in smaller or simpler distribution networks. At the bottom level is made up by field terminals which consist of FTUs & RTUs present in key points of distribution network, e.g., pole-mounted switch, transformers etc. These devices do the direct data gathering and issue the control command. Importantly, they have local intelligence, being able to do the fault isolation and service restoration on its own. the System becomes safer, when communicating failures. These three layers integrate seamlessly with each other using their own dedicated communication network, this allows the needed two-way data flow for the advanced feeder automation and best grid management [4].

3.2. Core functional modules (e.g., SCADA)

It's the bottom tier of the data foundational level, dependent on SCADA. SCADA gives the basic observable conditions and controllable conditions to the entire distribution network. It regularly acquires essential data like circuit breaker condition and line electrical parameters (like voltage, current, power and so on), via RTUs/FTUs that have been installed at different places within the network, then sends the gathered data up to the main station. It is also the downlink transmission channel used to execute dispatching operation commands, which can be remotely controlled by the entire network, and provides necessary data source and operational basis for all upper-level advanced applications: [5].

The application is feeder automation which gives power grid strength through SCADA as it forms the base support system. It usually appears as FLISR function do Fault Location Isolation & Service Restoration. This module can reduce the time of outage and lower the damage caused by short circuit of the grid, and grounding fault Logical Steps: First use the electric quantity changes that can be detected by the fault indicator or the terminal unit to realize the fault detection and sectioning, and then the system automatically sends orders to the switchgear on both sides of the faulty section to achieve the electrical isolation of the faulty point, and finally, through smartly rearranging the network topology, the tie switch takes over the load, so that the users without faults can quickly restore the power supply. , for all I need to do is wait it go on doing automatically troubleshooting, and many key indexes such as SAIDA become much better:.

These key functional elements can be put together in one single advanced system platform known as Distribution Management System (DMS/ADMS). It not only enhances SCADA function, but it is also the main part in higher level programs like Network Model Analysis, State Estimation, Power Flows, and FLISR. when working together on DMS/ADMS, DAS modules become the smart center

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for modern distribution networks, helps to achieve proactive grid maintenance, making asset management more efficient and advancing to smart grids

3.3. Information interaction and communication technologies (e.g., fiber optic IP network)

From an operational and information efficiency perspective, a DAS is very much dependent on a good form of communication architecture which brings together the two forms of connection (the wired and the wireless) at the same time as seen in Figure 2 below. This network infra has mostly been separated into 2 main modalities. Wired connection is the core part of the system, it's reliable all by itself and can withstand interference. Of all the wired options, fiber-optic communication stands out on the most vital backhaul links because it provides the greatest bandwidth, lowest latency, and most robust electromagnetic immunity. However, its great capital expenditure and long period of laying off often can't be practically accessed by terminal. Power Line Carrier (PLC) is a kind of complementary technology that takes advantages of the existing power distribution networks to provide transmission service and thus give an economic and easy solution. It suffers from a sensitivity to channel noise, and signal loss and attenuation.

Whereas wireless is very flexible, can be implemented very quickly, which makes it ideal to have an end point last mile connectivity to field devices in areas which might be remote or difficult with topography. Wireless networks are broken out into public networks like 4G/5G cellular, which are widely available and have very low operational costs, and private networks (e.g., WiMAX), which deliver enhanced security, dedicated bandwidth, and guaranteed Quality of Service (QoS). Notwithstanding their advantages, wireless channels are susceptible to interference from environmental factors and electromagnetic phenomena. Consequently, ensuring transmission reliability and security is paramount, necessitating the implementation of robust technical safeguards such as advanced encryption protocols and network redundancy [5,6]. Therefore, modern distribution automation systems often adopt a hybrid network model, which combines multiple technologies such as optical fiber, power line carrier, and wireless communication, so as to find an optimal balance point in technology and economic benefits, and realize real-time, reliable and secure information exchange of the system.

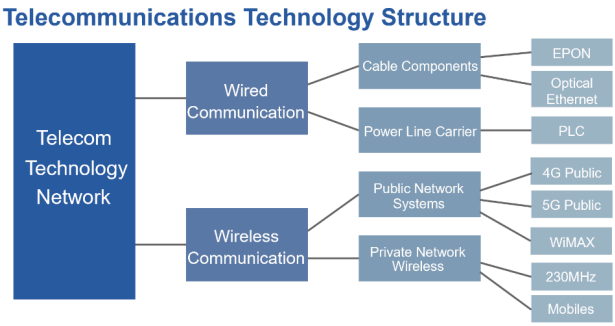

Figure 2. Integrated network architecture of communication technologies for Distribution Automation Systems

4. Key technologies and case studies

With the large-scale access of distributed generation and the ever-changing energy needs of users, modern distribution networks are evolving from traditional radial passive networks to more active, flexible, and intelligent distribution networks, as shown in Figure 3 below. To achieve this

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transformation, its operation and control system must be built around some core objectives, which aim to improve the performance of the power grid in all aspects. These goals can be summarized as follows:

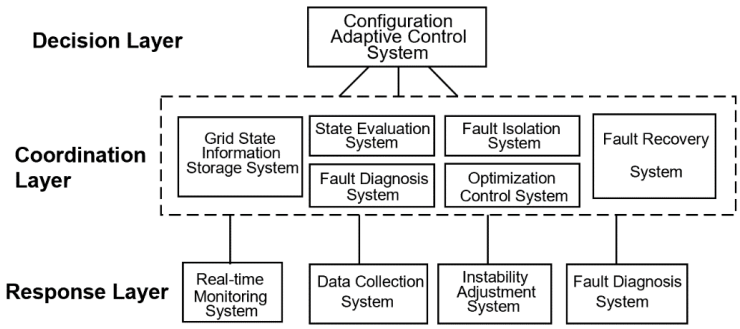

Figure 3. Schematic diagram of the smart distribution network structure

4.1. State estimation and simulation: the foundation for achieving grid visualization (fast simulation technology)

As power systems now evolve toward higher dimensionality, stronger nonlinearity, and greater uncertainty, traditional analysis methods based on static models and offline simulations can hardly meet the needs of intelligent dispatch for modern power grids. Therefore, Fast Simulation and Modeling (FSM) technology has emerged and is widely recognized as a core technology for future intelligent power grid dispatch and wide-area protection systems [7].

The meaning of FSM is much more than just about 'modeling' and 'simulation' literally. It is a high-level software system which combines together real-time state estimation, dynamic risk evaluation, self-healing control and operation optimization in a deep way. This can be seen as an intelligent upgrade for general EMS and DSM, and FSM is like the 'brain' of smart grid, with its main job being to give grid operators the 'precognition' ability. It not only presents accurate real-time snapshots of the system state but also produces forward-looking projections of the system's future states using real-time and historical data. When system is disturbed or breaks down, FSM can react fast through high-speed simulation and deduction, giving best decision help for stopping accidents, emergency control and even system recovery.

The technology's essential value is using computational speed to achieve predictive power; by simulating grid dynamics faster than they occur, it enables a shift from reactive analysis to proactive control. Changing from 'just reacting' to 'taking action first' is the key to keep future complex power grids safe and stable, and 'Digital Twin' is now the best example showing how FSM technology works.

Domestic and International Case Studies:

1. International Case: EU ERI Grid Project – Joint Simulation of Distributed Laboratories. The ERI Grid project, funded by the European Union's Horizon 2020 program, interconnects 21 leading smart grid laboratories across Europe to form a pan-European "digital twin" research platform [8]. The core of this project is the use of FSM technology to achieve cross-regional "system-level hardware-in-the-loop" testing. For example, the real energy storage hardware in one laboratory can interact remotely in a closed-loop with the real-time power grid simulation model in another laboratory. This model greatly expands the scale and complexity of testing, enabling efficient

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verification of system-level control strategies for the entire European power grid, and promoting interoperability between equipment and standards in different countries.

2. Domestic Case: Tsinghua University – Real-Time Simulation and Testing Platform for New Energy Microgrids Top domestic universities are also using FSM technology for cutting-edge exploration. The real-time simulation platform for power systems in the Department of Electrical Engineering at Tsinghua University focuses on solving the control and protection problems brought about by new energy grid connection by building a digital twin model of a microgrid containing wind, solar, storage and other equipment [9]. Researchers connect independently developed controller hardware to the simulation system, simulating extreme conditions such as islanding switching and network attacks on a millisecond scale, thereby efficiently testing and optimizing the dynamic performance and security of microgrid control and energy management algorithms, providing key experimental verification methods for the development of new energy technologies in China.

4.2. Fault self-healing technology: core applications (including fault localization, isolation, and recovery, reflecting self-healing)

Distribution automation self-healing technology primarily centers on two key aspects: the accuracy of fault location and the speed of isolating and restoring the system after fault occurrences. According to Table 1, the self-healing technology makes fault handling time shorter from minutes to seconds, which is greatly lowering the power outage risks [10]. Also, the automation upgrades can help the power grid to be more cost-saving and stable in operation. By using high-level sensors and calculating methods, the system can quickly detect line voltage, current changes and switch movement signals, this enables the system to rapidly locate faults and prevent time loss due to erroneous operations. When the problem part is found correct, the automation terminal quickly starts the isolation function, using reclosers and circuit breakers to cut off the bad area from good grid, so fault no influence nearby lines and whole network stay safe. In restoration stage, upstream non-fault zones can use terminal's local control logic to do second-time reclosing power supply, but downstream zones need main station's overall optimization model for checking backup power routes, load sharing and economy factors, then make dynamic transfer plan. This kind of level-by-level working together not just cut down the power cut time to minutes, but also make it possible to trace back fault data for analysis, so that the maintenance guys can find out risk spots like equipment getting old or outside disturbances, and in this way the grid become smarter and more reliable for long time [11].

Table 1. Comparison of self-healing technology effectiveness

Index	Traditional Methods	Self-healing Technologies
Fault Localization Time	5-10min	<1s
Fault Isolation Time	10-20min	1-5s
Non-fault section recovery time	20-30min	5-30s
Power Outage Time	30-60min	<1min
Power supply reliability improvement	95%	99.9%
Economic benefit	Benchmark	Reduce losses 20-30%

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4.3. Optimal operation and control: advanced applications

Based on fault self-repair and to make sure power supply reliability, the smart distribution network's advanced uses is focusing on improve system's overall running efficiency, economic performance and renewable energy holding ability, becoming the smart core part of DMS/ADMS. Among these, Voltage-Var Optimization (VVO) goes beyond the old way of local, non-cooperative control which depends on substation tap-changers and few capacitor banks. It uses real-time measuring data and precise network models, applying high-level optimization methods to do overall coordination control for different reactive power compensation devices in the grid, with the purpose to reach two targets that is lowering total system loss and making voltage quality better, so can greatly cut down network loss and enhance the grid's capability to handle renewable energy changes [12]. As a particularly high-level application, the Distributed Energy Resource Management System (DERMS) functions as a sophisticated software platform for the end-to-end management of Distributed Energy Resources (DERs). Mainly aggregate and orchestrate different types of grid-edge assets such as rooftop PV, Battery storage system and Electric vehicles. it has got on one hand some function space which includes something of traditional VVO’s capabilities to sustain grid stability, yet that span is far broader: Key function is so that it can enable the coordinated participation of the aggregated electricity markets and utility programs. It is like sending them around to do things like cutting that peak and then filling in those little empty spaces. And then they could do neat things like make sure it’s the right number of times and maybe play around with how much power there is if they have to! The end game of a DERMS is to unlock the full economic and technical value of DERs, right from the start of generation, on the grids, to the end customer loads, storage assets [13].

4.4. Wide-area measurement and control technology: the key to supporting the above applications

The implementation of the aforementioned advanced applications fundamentally relies on the accurate, high-frequency, and synchronized perception of the power grid state, which is precisely the technical advantage of Wide Area Measurement Systems (WAMS) centered around Distributed Phasor Measurement Units (D-PMU). Compared to the second-level asynchronous data of SCADA systems, D-PMUs can synchronously collect voltage and current phasor information of each node with microsecond-level time resolution and frequencies up to hundreds of times per second, bringing technological innovation to distribution automation. This high spatiotemporal resolution data stream can significantly improve the accuracy and speed of state estimation, providing a more reliable decision-making basis for advanced applications such as VVO and DERMS, and achieving a true restoration of network dynamics. In addition, by analyzing the transient phasor data at the moment of a fault, D-PMUs can achieve faster and more accurate fault location than traditional methods, and improve the efficiency of root cause analysis of events to a new level [14]. Therefore, wide-area measurement and control technology represented by D-PMUs constitutes the "neural network" connecting the physical power grid and upper-level advanced applications, and is the fundamental technical guarantee for realizing comprehensive and automation of the distribution network.

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5. Existing problems and improvement strategies

5.1. Main problems: system design flaws, uneven development, insufficient technological perfection, talent shortage

The adoption of distribution automation technology faces several bottlenecks that limit the smart grid's overall performance.

First, system design flaws and technical immaturity are prominent. Many older networks were not designed for automation, creating a gap between their architecture and modern standards. the aging infrastructure cannot handle fast data and smart sensors. it leads to a hardware problem. And they are not standardized, systems of different vendors are not compatible. it is not only lacking the most basic infrastructure, but also an immature ecosystem of technology that cannot be put into full use [15];

The second is that development is very unbalanced. As a result of disparities in regional economy and investment, the level of technology adoption differs widely. Developed area has a large size and advanced management. But, on the contrary, many rural and backward areas are very far away, some have no automation at all. And also this 'technology gap' holds back the grid's overall modernization, finally a paucity of skilled experts. Distribution automation is inter-disciplinary with power engineering, communications, and data science. it calls on people with extensive expertise but there's no many organizations that can become gurus in a traditional power system as well as new IT technology system. Consequently, advanced systems are often underutilized or improperly maintained, which compromises performance and long-term stability.

5.2. Solutions: build a unified information platform, optimize departmental collaboration, integrate internet technology, strengthen infrastructure and personnel training

To solve the distribution automation problems, we would need a plan. They include top-tier design, new technology, resource planning, and talent growth. First, we have to build a unified information platform and learn how to work as a team. Need a standard/unified platform. And it breaks between the divisions and departments and improves workflow. This means working well with the common information [16].

Second, we have to merge new techs with better infra. We have to use technologies like IoT, big data and edge computing. And it has to be done along with upgrading power grids and communication systems. It is good foundation for advanced tools.

Finally, it's about training good people. We have to cultivate a routine to train for and find talent. That way we get teams, that know both power systems and modern I.T. So it's used well for a long time and benefits us most.

6. Conclusions

In this paper, it has studied DA technology applied to smart grids. First of all, the core features of smart distribution networks are clearly defined, then the requirements for operations are clarified: it is necessary to connect to the network a very large number of DERs and to ensure that the electric power supplied is of good quality. Secondly, it's about the analysis concerning the distribution automation system's layered architecture, "master station – substation – terminal" makes up its parts, as well as key functions including SCADA/FA/DMS, also makes use of mixed networks fiber/PLC/wireless. Third, this chapter primarily introduces key technologies such as FSM, FLISR,

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VVO, DERMS, as well as the wide-area monitoring and control function of D-PMU. Through studying the EU ERI Grid project and Tsinghua microgrid platform cases,it can prove that both can make the grid stronger and run better,can see clearer and can see more clearly. At last, to solve problems like system design falling behind, development not balanced, technical compatibility not enough, and lacking talents, it gives solutions such as establishing a unified information platform, better teamwork between departments, combining IoT/big data, and training more skilled people. And these studies fill the gap between tech research and real-world engineering use, provides both theory and implementation methods for standardizing and smart-upgrading distribution automatic systems too. In the end it makes distribution network changing from passive to active smart, reaches both energy-safety and highly efficient use. Looking ahead, future distribution automation will be able to leverage AI and data to become an “autonomous grid-brain” to shift from reactive fault response to proactive risk prevention.

Looking forward, the future of distribution automation is to use AI and big data to enable distribution automation to be an autonomous "grid brain". This will make the transition from "reacting" to faults to "anticipating" the risks.

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