How to Build Smarter Electrical Substations by Mimicking Biology

by Pierre-Michael Schmitt
Georges Barbarin
Edward Jarvis

Executive summary

Those responsible for risk mitigation at utilities and other electrical distribution networks can take a degree of inspiration and guidance from human biological mechanisms, especially the human nervous system. Employing some level of biomimicry during switchgear modernization in the deployment of sensors and connected substation technology pays off in numerous ways. Those include better energy efficiency, superior asset performance management, extended equipment lifespans, protection of capital investments, and improved service continuity—even by retrofitting existing equipment.

Introduction

Risk management

What is risk management? Let's begin with a straightforward definition. According to ISO 31000[1], risk management entails "the identification, assessment, and prioritization of risks (defined in ISO 31000 as the effect of uncertainty on objectives) followed by coordinated and economical application of resources to minimize, monitor, and control the probability and/or impact of unfortunate events or to maximize the realization of opportunities. Risk management's objective is to assure uncertainty does not deflect the endeavor from the business goals."

In the electrical distribution domain, two very clear drivers of risk mitigation or management are the threat to the reliability of power networks and consequentially the goal of avoiding the substantial expenses incurred by outages that cause production shutdowns.

Table 1

Financial impact of one hour's production shut-down

Source: Contingency Planning Research and Schneider Electric

Application	Loss(*) in €
Health establishment	Human lives
Stock market transactions	6,500,000
Credit card sales	2,600,000
Petrochemical	100,000
Plane ticket booking system	90,000
Mobile phone network	40,000
Automobile	30,000
Pharmaceutical	30,000
Food processing	20,000
Cement	15,000

Which risks to manage

For electrical distribution equipment at the substation, of which switchgear forms the heart, care must be taken to minimize the likelihood of the various situations that lead to equipment failure. The following are the top five causes of switchgear failure[2]:

- Loose connections
- Insulation breakdown
- Water/humidity
- Breaker racking
- Faulty ground fault protection

The means through which risk to substation equipment is minimized are design engineering and technology modernization, sound maintenance strategies, and appropriate levels of service.

---

[1] ISO 31000

[2] *No-Outage Inspection Corner, Don A. Genutis, Group CBS*

Human biology's strategy applied to electrical installations

Like physical, inanimate equipment in the field, our own bodies must also mitigate the risk of system shutdown to give the organism (us) the best chance of continued operation (life). The innate biological mechanisms employed by our bodies also utilize different maintenance strategies and service delivery vehicles to make sure we're up and running in an optimal way.

Different circumstances, different actors

Think back to biology basics and consider the human nervous system. You've got a central nervous system composed of brain and spinal cord, and a peripheral nervous system which is normally categorized into two systems: the somatic and autonomic. The somatic controls things we can do voluntarily, like move skeletal muscles, and the autonomic covers the involuntary, like heartbeat regulation.

An analogous ecosystem in the electrical distribution context contains similar layers, each of which must communicate with the other. There is foundational level of hardware, equipment and assets in operation in the field, composing the physical grid itself and capable of upstream communication, much like the heart or other organs that are fundamental to an organism's existence. A step up from field equipment is edge control, which are systems that connect to, coordinate, and manage the way field equipment works, much in the same way the autonomic nervous system communicates with its downstream organs. At the highest level are the grid apps, analytics, and services that feed the edge control systems with data and the means to make the best possible decisions based on information collected from the rest of the system. This mirrors the functions of the brain, whose job is identical.

In humans, the somatic and autonomic nervous systems comprise a magnificent array and staggeringly large volume of cells whose purpose is not only to act as sensors but also manage the feat of communicating information to and across the other components of the nervous system and with the primary control center, the brain.

In the distribution grid, connected equipment capable of communicating upstream and downstream of their location and with the control center is also crucial. Data about equipment status and knowledge of network state must be shared not only with the control center, but also with neighboring devices.

The human autonomic nervous system itself has two parts: the sympathetic and parasympathetic nervous systems. The former is generally thought of as responsible for 'fight or flight' types of reactions, and the latter is often categorized as the one responsible for 'rest and digest' mechanisms. Both contain sensory neurons that send signals back to the central nervous system and brain, and motor neurons for signals traveling in the opposite direction to drive appropriate actions.

Viewed another way, one responds to emergencies immediately, while the other takes or more measured, considered approach.

The same antagonistic (or complimentary) strategy can be seen in electrical distribution applications, for example in an electro-intensive oil and gas exploration process. The equipment has more than one job, and they are in conflict. It's the equipment's purpose to keep good-quality power flowing without interruption, ensuring maximum uptime, because even the shortest shutdown is punishingly expensive. But the equipment must also be willing to ignore that fact when there is a potential safety issue, and help ensure that its operators and other equipment is not in danger of harm.

Sense and sensibility

We have our nervous system to thank for thorough sensory perception, among other things. It manages the collection of important information about the condition and state of the organism to which it belongs.

In electrical distribution systems, particularly in substations, modern smart grid technology is accomplishing the same thing. In medium-voltage switchgear, for example, distribution grid operators can take advantage of a variety of sensors that detect and communicate information about the equipment, such as thermal information or humidity conditions. These sensors provide grid operators and the technology they use with a strong situational awareness of the state and health of grid equipment.

In humans, one particularly interesting detail of this vastly complex communication and control network is the allocation of nerves, and the amount of resources dedicated to processing the information they send. Sensory nerves are located in many places, but highly concentrated in the places where they are used most and the most information is required, such as in our hands and in sensory organs we use to perceive the world.

In electric distribution grids, sensors accomplish these goals of measuring and transmitting data to be analyzed into useful, actionable insights. They also tend to be located in the places where they are most needed, which is often within substations and the equipment operating therein. Protection relays, for example, sample and measure relevant equipment values such as current and voltage characteristics and trigger downstream or upstream network responses when values deviate from acceptable levels defined by their configurations.

But where these sensors are concentrated is more interesting. In an electrical substation, sensors need to be deployed wherever there is a high probability of issues occurring:

- To protect against short circuits, the protection relay is in the switchgear
- To indentify bad or poor connections, thermal sensors are placed near junctions
- To monitor corrosion and humidity, sensors are on the low-temperature side of the equipment or in the substation

And what about the rate at which data is collected? For information to be useful, the frequency of data acquisition and data accuracy are linked to the speed of change of the phenomenon. This is true of both measurements taken of the human body and of substation distribution equipment.

For example, someone feeling sick might take Paracetamol to treat fever symptoms. But changes in body temperature occur slowly, so it is not useful to measure one’s temperature more than once every thirty minutes to measure the impact of the drug on the fever.

In short circuit protection, on the other hand, a protection relay samples 10 to 1000 times faster than the phenomeneon itself. For thermal changes, sampling is by the minute, whereas corrosion humidity sensors sample every 5 minutes.

Responding to stimuli

Consider the body's approach to incident response. The first item in the order of operations is an event, some sort of occurrence that disrupts the normal state of operation. A hand accidentally placed on a stovetop's hot burner, for example. The ability to notice this abnormal and potentially damaging event is the first step, which the nerves sense and respond to.

This first layer of decision making can take place via a reflex arc without the consultation of the brain, in order to provide the most expedient possible response in a potentially dangerous situation. This very fast and reasonably local decision-making layer informed by thermal sensors in the skin causes the rapid removal if the hand from the heat.

Humans face other circumstances that require management action, but with less instantaneous urgency. Thermal regulation, for example, nicely illustrates a monitoring and control mechanism that requires some central oversight by our brain. In order to maintain a constant internal body temperature despite changes in the ambient temperature and other variables, our bodies use a range of medium-speed strategies, many of which are governed by the hypothalamus. Acting as a thermostat, this organ connects via nerve cells to thermoreceptors elsewhere in the body and coordinates the necessary response to maintain the correct temperature: e.g., sweating for evaporative cooling, shivering to generate heat, or even behavioral actions like taking off or putting on a sweater.

We see analogies between the reflex arcs that occur without central control and the peripheral/central nervous systems in the human body, and the localized field equipment vs. central control and SCADA systems of modern electrical distribution grids. For example, there is fast-acting substation equipment that can take emergency measures independently, but higher-level, longer-term decisions require some coordination from the control center, i.e., the brain.

The nature of the response to distribution network events depends on the nature of the event itself, and the likely severity of the consequences of the event. The layers of decision-making vary accordingly.

For example, for fast, high-criticality, high-impact and unexpected phenomenon, sensors, decision processes, and actuators are bundled together to increase communication speed and reduce communication errors, reaction times, and risk of colliding information within the network. This could involve a mostly dedicated system like a protection relay preventing a short circuit. Arc-flash protection is another example.

For medium speed phenomenon like the unexpected shutdown of one of the two utility supply feeds, the network reconfiguration is managed by upper layers. The same would be true in the case of a loss of power causing the activation of a UPS, which in turn causes the startup of a diesel generator, or even a second diesel generator as a redundant third line of defense.

For slower phenomena with a minimum impact on the process, such as the unexpected increase of energy consumption, data can be analyzed remotely by smart software or services that provide corrective mechanisms. Some phenomena require lengthy sampling or measurement periods in order to detect or diagnose detrimental irregularities before launching an appropriate response.

Energy consumption analyses don't necessarily require fast acquisition of energy consumption data. These analyses are based on hourly, daily, or weekly time ranges, and corrective actions are taken in the same time frame.

Healing and repair operations

Let's look at the some of the ways our bodies go about the process of healing and repair, and how smart substations and electrical distribution equipment can do so in a similar way.

In humans, healing and repair take place in response to injury, but also on a regular basis, to keep the organism functioning in an optimal way. The skin, for example, our largest organ, responds to injury in three main steps, highly simplified here. First is inflammation, during which blood clotting takes place. This is an emergency response having little to do with repair, but rather preventing further damage and stopping blood loss. Next comes proliferation, where new tissue grows to replace the old. Finally comes maturation, where the scar tissue is remodeled to become as strong as possible.

Electrical equipment also has built-in mechanisms for ensuring the health of the organism, which in this case is a power network. On high-voltage lines in rural areas, for example, stanching the blood flow means clearing the fault as fast as possible. Vegetation interfering with powerlines can be quickly burned off by high-voltage pulses, avoiding downtime. In a distribution substation, capacitors can take advantage of the self-healing insulation of metallized film capacitors, whose faults or short circuits in their own dielectric film vaporize the metal electrodes surrounding the defect and isolate that part of the insulation. In both scenarios, the goal is to immediately return the network to a functional state.

Further, during regular, everyday life, and in non-injury scenarios, our bodies also conduct regular maintenance. Each part of the human anatomy has its own distinct lifespan. Our stomach lining, operating a harsh environment, is refreshed roughly every few days. It takes at least a decade, however to fully renew our bones. Other parts of our bodies remain with us from the day we're born and do not change.

Electrical distribution systems are similar in that different maintenance strategies are demanded by different parts of the system. And like our bodies, more maintenance is required as equipment ages. Distribution network operators strategically schedule and employ a variety of practices to maintain electrical distribution equipment to get the most out of the system. Foremost is uptime and safety, followed closely by energy efficiency and cost management.

Some injuries and diseases surpass the limits of what's reparable via biological response. Accidents, incidents, and diseases can render the ongoing functioning of a biological system or organ impossible without outside assistance. In this case, one approach is transplantation. It's not uncommon for heart and liver transplants to further the lifespan of those in need, and advancements in these fields are constant.

And in distribution systems as well, repair is not always possible. The best possible outcome can involve an upgrade, through the modernization of equipment via retrofitting, or the replacement of certain devices and hardware. Like modern medicine, technology advances further every day, opening new possibilities in terms of asset management, service continuity, and efficiency.

Implications, guidance, and data

Modernization upgrades open the door to enhanced equipment connectivity, leveraging new sensing technologies. This allows access to more detailed levels of energy efficiency, asset performance management, and energy quality data. Analytics are then made available. Furthermore, the association of sensors and algorithms enables the detection of premature equipment aging.

The path to modernization

Like humans, electrical distribution networks are complicated ecosystems that require guidance and treatment from trained professionals who specialize in improving and maintaining those systems.

The best starting point is always a check-up, in order to gain an understanding of the current state of the system. Equipment manufacturers are especially well positioned to conduct in-depth assessments of electrical distribution networks to identify weaknesses, inefficiencies, potential sources of cost savings, and points of beneficial enhancement that will affect not only network health but also the health of the businesses that depend on them.

In all cases, regardless of current symptoms, achieving optimal electrical network efficiency and all the benefits of a strong asset management program demands a strategic approach to electrical distribution equipment and modernization, especially for substation equipment.

To reduce the risk of equipment failure and shutdown, old substation technology can be upgraded and modernized. The installation of connected sensors can make a substantial contribution toward achieving the numerous operational and financial benefits of modernization. The spectrum and purpose of substation sensing technologies, which can often be installed by the relatively simple retrofitting of existing equipment, is improving continually. Like the development of vaccines, pharmaceuticals, or medical technology, the most probable, solvable, and detrimental problems are tackled first, and afterward specialized sensors and analytic technologies seek to address rare conditions to decrease the probability of failure. These connected (or connectable) and digitized devices offer various types of monitoring, including thermal, humidity, usage and condition-based monitoring.

These sensors can monitor all critical points, including circuit-breaker connections and busway joints and connections. And that monitoring takes place in real time, which helps modernize maintenance practices and transition from basic time-based maintenance to condition-based maintenance. Further, these sensors do not compromise the internal arc withstand, and never sacrifice safety for convenience. They can also communicate wirelessly, so there's no danger of maintenance operations damaging associated communication cables or fiber optic lines.

Design guidelines

Visibility and real-time understanding of network state and equipment health are prerequisites to effective grid management. This means that where sensors are deployed on the network, as well as the depth and breadth of information and the frequency with which they collect and transmit it, all play key roles in determining how much value can be added to a given system.

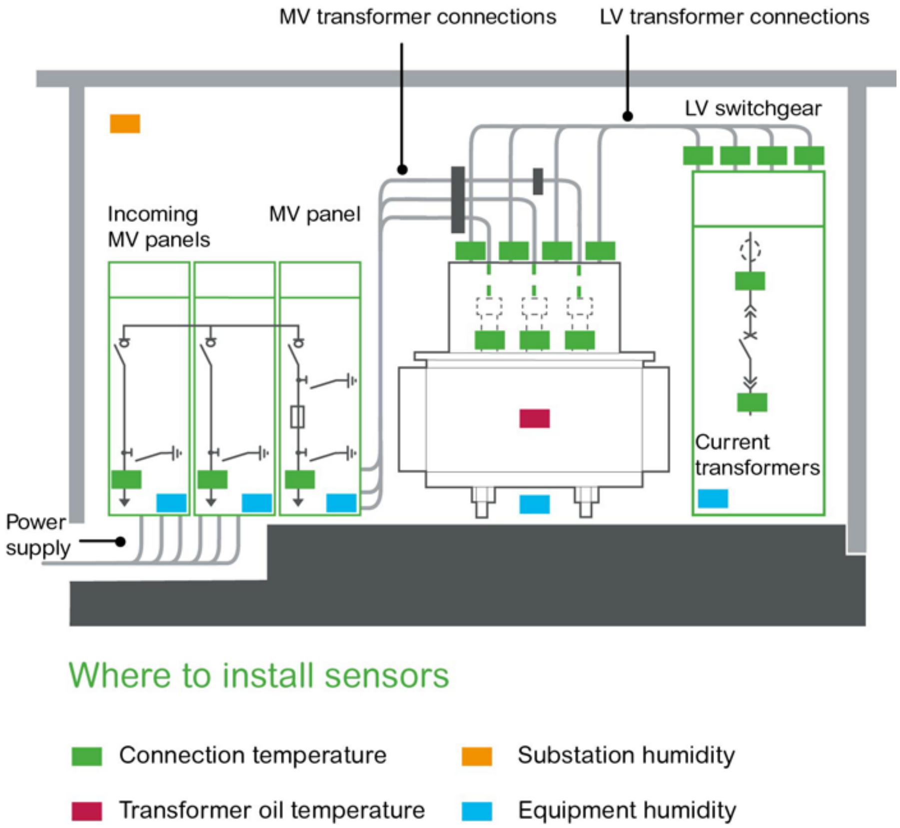

Figure 1

Recommended sensor placement in substation

The beneficial results of such systems can go far beyond merely coping with network complexity and integrating greater amounts of variable renewable generation sources into a distribution grid architectures that were never design to do so. It also unlocks the ability to achieve previously unheard-of levels of operational efficiency and reliability, and opens doors to strategic maintenance practices that strengthen these benefits to an even greater degree.

The data collected by these sensors feed the rest of the system. First; they can be exchanged with other upstream and downstream devices at the level of connected equipment in the field. From there, these data move up to be consumed by edge control systems, such as an Advanced Distribution Management System (ADMS) where they fuel the intelligence of apps, analytics, and services to enable modern, digital distribution networks to fulfill the promise of unprecedented network efficiency. That top level can include special grid analysis modules that plug into ADMS, such as those that model peak shaving and demand management, or others that make proactive and predictive maintenance strategies a reality.

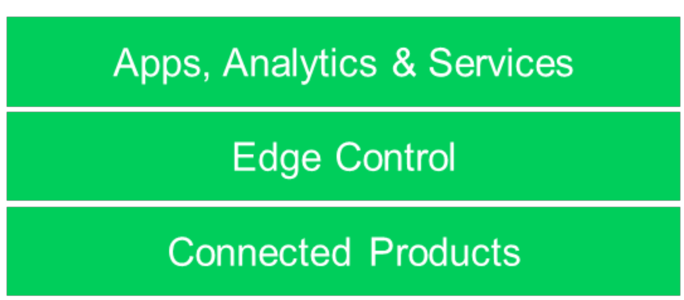

Figure 2

Technology and innovation stack

Conclusion

Substation engineers and risk managers can take inspiration from our own clever biological systems to inform the design and management of electrical distribution networks and the equipment therein.

When they do, they find retrofit solutions that equip substation equipment with sensing technologies and connected digital features. Such modernization and monitoring opens the door to stronger levels of grid efficiency, asset performance management, and energy quality, and is accompanied by cost savings, extended equipment lifespans, protection of capital investments, and most importantly, reduced shut-down risk.

About the authors

Pierre Michael Schmitt, PhD, is the Modernization Automation Offer Manager at Schneider Electric. He is an electrical engineer specializing in sensors and energy conversion. He earned a Ph.D. from the Department of Biomedical Microsensors and Microsystems at the National Institute of Applied Science in Lyon, France. He previously worked on the study of interface parameters of the human body: flexible sensors for the measurement of interface pressure for secured forceps, matrix of interface pressure sensors for seats, beds, etc., for the prevention of pressure ulcers. He studied the relationship between interface pressure and autonomic nervous system activity. Dr. Schmitt received the first award in the Rhone-Alps region for biomedical research in 2004 and the award from SFGBM (French Society for Biomedical Engineering) in 2005. For the past seven years, he has managed and developed global digital services links to energy efficiency and asset management.

Georges Barbarin is a Senior Marketing Manager in the Schneider Electric Field Services electrical distribution business unit. He holds a Bachelor Degree in International Business Administration in Management and over the last 25 years has held numerous industrial and marketing positions within a variety of business units and international operational divisions. As expert in operational marketing and business development, he has recently helped develop the modernization of electrical distribution switchboards business within Schneider Electric and is currently implementing standard and customized retrofit solutions across all geographies.

Edward Jarvis is the Technical Information Manager for Automation at Schneider Electric. A graduate of Colorado State University, he's traversed the utility industry, having held numerous technical communication roles in businesses serving electrical, telecom, gas, water and wastewater utilities. From instructional design to product development to marketing communication, he's dedicated to developing, cultivating, and delivering useful and interesting information for those who build, operate, and maintain critical infrastructure.