Homeostatic Control and the Smart Grid: Applying Lessons from Biology

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Abstract Electric power grids in this country and abroad are undergoing revolutionary changes through the increased integration of electric power generation, delivery and consumption with computation, communications, and cyber security. Emerging out of these activities is a smart grid that includes new technologies ranging from microgrids capable of islanded operation to wind power generation and electric vehicle supply. The success of this massive endeavor will depend on large measure on the development of control methodologies that maintain homeostasis in the face of natural stresses, malfunctions and deliberate attacks. The goal of this chapter is to sketch out possible control strategies for the future smart grid based upon insights into how living systems deal with these same issues. This is a broad topic and the particular focus here will be on presenting a simple model of control by neural and innate immune systems that could be applied to operational security at substations and microgrids.

Keywords Operational security · Innate immunity · Neural control · Multi-agent systems · Substations · Microgrids

1 Introduction

Smart Grids have their beginnings in the pioneering work of MIT professor Fred Schweppe. Writing in the 1970–1980 timeframe he introduced the novel ideas of homeostatic utility control (Schweppe et al. 1980), in which pricing depended on system conditions and is dynamically adjusted, and household appliance load set-points that are adjusted according to system frequency. These notions have their

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culmination in the modern conception of smart meters, which along with microgrids capable of islanded operation are key elements of modern smart electric grid projects now underway throughout the world. These developments are driven by declining energy resources and increasing demand, and by the desire to develop green technologies. Smart meters have been now joined by smart appliances, smart houses and the smart grid, and by wind power and electric cars plugged in at homes and elsewhere serving as reservoirs of electrical power.

Electrical grids are subject to a variety of environmental and internal stresses including human error leading to supply-demand load imbalances, frequency drift and, in worse cases, cascading blackouts. Power systems increasingly operate under highly stressed conditions, and as a result blackouts may be triggered by any of a number of forms of instability. Cascading failures may be triggered, for example, by a loss of voltage or frequency stability, by a combination of the two, and by inter-area oscillations (IEEE/CIGRE 2004). Additional stresses and failure modes become possible due to the integration of communications into the grid making increasing likely deliberate attacks by cybercriminals and agents of hostile nation-states.

Valuable insights into weaknesses in the present electric grid are provided by studies carried out during the past ten or fifteen years of their physical, i.e., topological, properties. An important finding from these studies (Sachtjen et al. 2000; Albert et al. 2004) is that the links between nodes in man-made networks such as the power grid are not normally distributed with most of their links centered about some average value. Instead, the distribution of links follows a power law in which most nodes are connected by just a few links and there are a significant number of highly connected nodes. It is then observed that the electric power grid is exceptionally vulnerable to disruptions in its highly connected nodes. These disruptions can trigger a breakdown of an entire network, fragmenting it into isolated patches. In networks such as these, large-scale blackouts are far more common than would be the case were the probability distribution functions to have conventional exponential tails. This situation is exacerbated by a second key feature of these networks. They typically operate close to a critical point; i.e., close to their operational limits (Sachtjen et al. 2000; Carreras et al. 2004). The power system networks are thus doubly susceptible to cascading failures brought on by deliberate attacks (Dobson et al. 2007).

1.1 Need for Operational Security

Operational security—the investigation, mitigation and recovery from stresses, perturbations, and disruptions, both transient and longer lasting—is a major requirement of the smart grid. To achieve operational security, in other words, to maintain homeostasis, the smart grid must be capable of sequentially carry out the following operations:

- Rapidly detect and respond to loss of homeostasis
- Limit local damage when it occurs

- Initiate inter-site communications
- Prevent cascading failures
- Recover and return to normal operations.

Adding to the urgent need for operational security is the growing threat of cyber-attacks. A noteworthy event in this regard was the emergence of the Stuxnet Siemens worm in early 2010, the first publically recognized malware attack of a supervisory control and data acquisition (SCADA) system. Disruptions of this kind have become ever-more likely due of the strong integration of the power system into the Internet and the widespread use of commercial off-the-shelf (COTS) software in the power grid's control systems. The creation of a smart grid with multiple, readily accessible entry points for insertion of malware will only increase the frequency of disruptions of this kind.

1.2 Goals of this Chapter

The goal of this chapter is to apply to the smart grid lessons learned from studying how biological organisms deal with the loss of homeostasis brought on by pathogen attacks, stresses and injury. Recall that in higher organisms such as us there are two types of responses to invasion by pathogens. The innate immune response develops rapidly, and promotes formation of a protective and isolated environment for clearance, repair and recovery of the damaged tissue. The adaptive immune response develops slowly over several days; it involves generation of antibodies and activation of B and T cells to provide long-lasting immunity. The adaptive immune response is unique to vertebrates, while fungi, plants and animals possess a rapid response system to the onset of infection and tissue damage. Our focus in the chapter is on the rapid response, innate immune system.

In humans there are three super-systems—the immune, nervous, and endocrine systems. Contrary to popular thought these systems do not act independently of one another but rather are interconnected and continually communicate and regulate one another. In particular, the nervous system provides central homeostatic feedback control over the actions of cellular agents of the innate immune system such as macrophages and neutrophils. Acting together, the innate immune and nervous systems provide a coordinated response to stress, injury and invasion. We will begin our exploration with a brief overview of how the nervous system provides central control over the innate immune system. We will then discuss the inflammatory response and multi-agent systems, and introduce a simple neuro-immune model for enhanced operational security at substations and microgrids.

2 Central Control by the Nervous System

Central control over innate immunity by the central nervous system is present in all creatures, great and small. For instance, the nematode worm, *Caenorhabditis elegans*, possesses a primitive nervous system containing just 302 neurons. Yet, it was found recently (Sun et al. 2011) that neurons in *C. elegans* monitor the inflammatory response and limit its effects arising from pathogens and injury. These neurons provide negative feedback control and maintain innate immunity homeostasis. The nervous system in humans is, of course, far more complicated and regulates the innate immune response through multiple hormonal and neural pathways (Sternberg 2006). It fosters communication with the innate immune system by sharing many of the same chemical messengers (Blalock 1989). It monitors the molecular products of pathogen invasion and the presence of cytokines, the main chemical messengers used by the innate immune system. Once activated, the nervous system first potentiates the immune response and then working through negative feedback loops it damps down the immune response and restores homeostasis within the community of innate immune mediators.

The two primary systems of neural regulators of innate immunity in humans are the hypothalamic-pituitary-adrenal (HPA) axis and the vagus nerve. The vagus nerve provides negative feedback regulation of inflammation through sensory afferent signals and efferent feedback (Tracey 2002; Wang et al. 2003). It is a large nerve (cranial nerve X) extending from the brain stem to the colon and containing numerous branches. It sends efferent output to many of the muscles/organs of the body and is involved in control of heart rate, breathing and digestion. The HPA axis is a neuroendocrine regulator of immunity (Sternberg 2006). This regulatory pathway encompasses the hypothalamus located in the brain, the pituitary gland situated below the hypothalamus at the base of the brain, and the adrenal glands located just above the kidneys. It regulates body temperature, energy levels and digestion, and the body's response to stress, injury and trauma through the fight or flight response. These actions are joined by contributions from the sympathetic and peripheral nervous systems that along with the HPA axis and cholinergic pathway (vagus nerve regulate innate immunity at the local, regional and system-wide levels (Sternberg 2006). This system of control is obviously a complex one with many outstanding questions on how it operates remaining to be uncovered. In Sect. 4 of this chapter, we will replace it with a far simpler and better characterized neural control system that could be used to regulate the actions of the electric grid innate immune system.

3 Innate Immunity and the Inflammatory Response

Everyone is familiar with inflammation, a key component of innate immunity. The inflammatory response produces fever and pain, and redness and swelling. A protected local environment is formed that limits spread of the infection, promotes the destruction of the invaders, and hastens the repair of the damaged tissues. Most importantly, the physiological changes in the local environment facilitate the convergence of white blood cells (leukocytes) to the site of the infection. These white blood cells, principally macrophages and neutrophils, are the cellular agents of the innate immune response. In the first phase of the inflammatory response, these agents destroy pathogens, and remove dead and dying cells, damaged support structure, and cellular debris. In the second, recovery phase, they help restore the tissue to a healthy, fully-functional condition.

Several kinds of cells—neutrophils, monocytes and macrophages, dendritic cells and mast cells—mediate innate immunity. In addition, there is a (non-cellular) complement system that assists the cellular component through the release of molecules that mark extracellular pathogens for destruction and, along with antigen-presenting dendritic cells and macrophages, activates the adaptive immune response. In the remainder of this section, we will consider a simplified system consisting just of macrophages and focus first on what they do (their patterns of behavior) and then on how they do it (sensors and platforms).

3.1 Macrophage Patterns of Behavior

The first features of macrophage behavior worth noting is that both circulating and tissue resident macrophagesare utilized in innate immunity. Examples of tissue resident macrophages are Kupffer cells (liver) and osteoclasts (bone), alveolar macrophages (lung) and microglia (brain). These cells are assisted by mobile, patrolling monocytes (macrophage precursors) and macrophages that converge on infected and injured tissue.

The second key observation is that macrophages are highly plastic and respond to environmental cues by reversibly switching from one phenotype (behavior) to another. They may carry out pathogen clearance and tissue cleanup responses when those actions are necessary, execute a repair and recovery program whenever that is needed, and perform regulatory tasks to prevent excessive responses if that is required (Mosser and Edwards 2008; Beckerman 2009). The third main point, already hinted at above, is that inflammatory responses are tightly controlled, and control over their agents is exerted at the local, regional and systemic levels by the immune and nervous systems.

Overall, there are multiple patterns of macrophage activity and their actions need to be carefully timed and coordinated—damage detection followed by isolation and cleanup followed by tissue restoration. In the smart grid, these would be replaced by the five action stages key to maintaining operational security listed in Sect. 1.1 and presented in the form of a bullet list.

3.2 Responding to Signals of Invasion and Injury

The seminal concept of innate immunity is that pathogens are detected by specialized germline-encoded sensors. This operational model was introduced by Charles Janeway in (1989). The sensors envisioned by Janeway were capable of detecting molecular patterns characteristic of not just one species of pathogen but rather whole classes of them. The pathogen-associated molecular patterns (PAMPs) are microbial components that are essential to pathogen survival and cannot be easily discarded or disguised.

In a further development of the model, Polly Matzinger (1994) proposed in 1994 that pattern recognition receptors (PRRs) not only respond to microbial PAMPs but also respond to non-microbial signals indicative of trauma and damage. These other signals are termed damage-associated molecular patterns (DAMPs). Under normal conditions, DAMPs are sequestered in cellular compartments away from the sensory apparatus but when the cells are sufficiently stressed they are released into the cytosol where they are detected and initiate inflammatory responses.

In the past ten years a third major development in innate immunity has taken place. Beginning in 2002 (Martinon et al. 2002) it has become ever clearer that macrophages utilize molecular platforms to response to signals of injury and invasion. These platforms, called inflammasomes (Martinon et al. 2002), bring together in one location PAMP and DAMP sensors, interfaces and the downstream initiators of cellular and system responses. Inflammasomes are positioned at strategic locations throughout the cell where they monitor crucial components (organelles) for indications of damage and malfunction. Utilizing a combinatorial code these response platforms generate the correct responses to the variety of signals being received at a given time.

Two observations provide further insight into how biological organisms respond to pathogens and damage. First, indirect detection of injury and invasion takes place. In these situations, the indicators that are being sensed are produced by the processes triggered by the causative agents, not the agents themselves. The products being sensed are produced rapidly, and their detection launches an immediate inflammatory response that limits the damage to a particular region, and begins the healing and restoration of homeostasis. In many instances, the key properties being sensed are inappropriate signaling and control actions. Second, in many cases, not one but two distinct signals are required to elicit an immune response, for instance, a PAMP and a DAMP. This is done to prevent premature and inappropriate immune actions.

4 Central Pattern Generators

Central pattern generators (CPGs) are elementary circuits built from a small number of neurons that generate the highly stable motor patterns responsible for activities such as walking, swimming, breathing, chewing and digestion (Beckerman 2005). Generation of these behaviors is autonomous—the circuits are self-contained, able to generate rhythmic patterns independent of timing input and sensory feedback. They are not only relatively simple but also readily accessible to experimental manipulation and produce easy to distinguish motor patterns (behaviors). CPGs were first studied a hundred years ago (Graham-Brown 1911) and in the ensuing time period have been the subject of numerous studies, experimental and theoretical, in species ranging from primitive invertebrates to mammals. They have already entered the engineering arena through their use in robotic movement control (Ijspeert 2008).

Several properties of these control circuits are desirable from perspective of the electric grid of the future. In this chapter, we propose that controllers with similar properties be adapted for use in the electric grid, not to generate rhythmic (motor) patterns but rather to work together with immunological agents to generate and coordinate operational security actions and endow the grid with resilience to malfunctions and deliberate attacks. In the remainder of this section, two properties will be examined. The first of these is stability, that is, the ability of these circuits to maintain constancy of output in the face of variability and breakdowns in components. The second is responsiveness, namely, the ability of these circuits to switch from behavioral state to another is response to modulatory signals from outside.

4.1 Redundancy and Degeneracy

To understand how these circuits maintain robustness in the presence of considerable variability in failure modes we have to distinguish between the terms “degeneracy” and “redundancy”. The latter term, redundancy, is a familiar one. It refers to the performance of a particularly task by multiple, structurally identical copies of some element(s). It is a traditional way of dealing with circuits and other structures build from fault- and failure-prone elements. Degeneracy differs from this in a fundamental way. In the case of degeneracy, a particular function is carried out by structurally different elements (Edelman and Gally 2001). That is, there exists multiple, non-identical ways to produce a desired output and in each instance one of these solutions is selected.

Several observations made during the past few years support the notion that biological systems extensively exploit degeneracy and not redundancy to achieve robustness and resilience to malfunctions and loss of components. The first set of observations supporting this model is that there is considerable variability in components, in the numbers and biophysical properties of their ion channels, from one neuron to another of a given type (Marder and Goaillard 2006). Furthermore, the circuits built from these component neurons are remarkably stable, in spite of considerable variability in strengths from synapse to synapse across the neurons. It appears that failures in some components are compensated for by adjustments in the response properties of other components such that the overall behavior of the neuron or circuit is preserved (Prinz et al. 2004).

4.2 Stability and Responsiveness

The second key property of these circuits—responsiveness—is built upon their ability to generate not just one but rather several different patterns, or behaviors, in their downstream targets. That is, they are capable of reconfiguring themselves, some components (neurons) becoming more strongly coupled in to the active circuits while

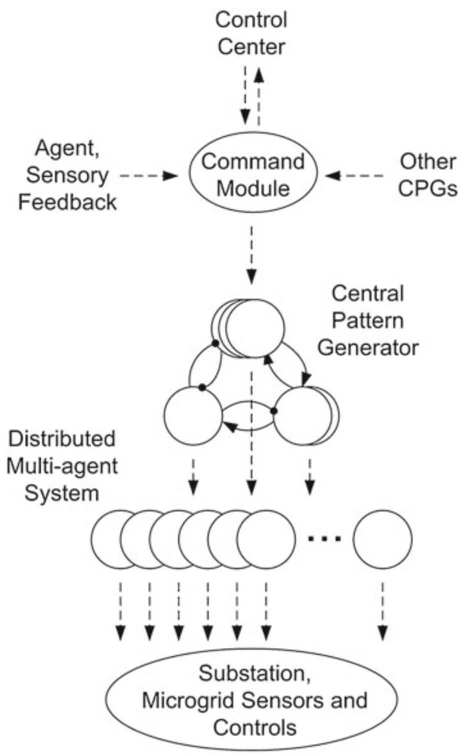

Fig. 1 Biologically-inspired control architecture for the smart grid. Signals supplied through the command module instruct the central pattern generator (CPG) on which pattern of activity to generate among the software agents. The software agents interact with SCADA sensors and controls in substations and their counterparts in microgrids, and supply feedback to the upstream controls. In this model, humans remain in the loop and can direct actions taken. In the CPG circuit, sharp arrows denote excitatory connections and filled circles represent inhibitory connections

others drop out entirely. By this means they can switch from one behavioral state to another, generating several different patterns, each pattern corresponding to a specific functional state on the part of the motor plant they control.

Most significantly, while each of the states is stable against malfunctions, the circuits are responsive to information coming in from outside the circuit. As shown in Fig. 1 the central pattern generator receives input from a modulator (command) module. This module integrates together a variety of signals that jointly guides the selection by the CPG of which pattern to generate. Included in the decision process are signals from other CPGs, from sensory feedback, from feed-forward signals conveying information about external conditions from central control, and from other modulatory signals which for our purposes can be regarded as conveying local information. Thus, these remarkable circuits manage to balance flexibility needed to respond to environmental changes, and to adapt to new demands, with stability against variations in underlying component composition and properties. These are properties needed in the smart grid.

5 Neuro-Immune Model of Homeostatic Control for the Smart Grid

Software agents appear to be an ideal way to incorporate macrophage-like inflammatory responses and innate immunity principles into operational security. This association is enhanced by the close match between the observed patterns of macrophage-inflammasome behaviors and the "bullet list" of necessary operational security actions. Multi-agent systems (MAS), i.e., systems composed of two or more software agents, have been proposed for some time as a means of achieving distributed control over macrogrids in a future smart grid (see (McArthur et al. 2007a, b) for a review of early MAS applications to electric power grid). The software agents in a multi-agent system are encapsulated computer programs capable of flexible, autonomous actions. They are (i) problem solving entities with well-defined boundaries and interfaces; (ii) embedded in specific environments, receiving sensory information about the state of their environment and acting back on the environment through effectors, and (iii) designed to act reactively and proactively in performing their assigned tasks (Wooldridge 1997; Jennings 2001).

As a first step in implementing biologically-inspired operational security, 'inflammasomes' would be positioned where they could monitor and control the operation of key components at substations and microgrids. Signals from these components would be monitored and integrated together at the inflammasome platforms together with signals and data from upstream CPGs in order to assess operating conditions and respond to inappropriate signals and abnormal conditions.

Overall, the combined neuro-immune system serves as an attractive model for the grid. A set of semi-autonomous distributed agents, macrophage-inflammasome (MI) agents, provides for local regulation of the grid with rapid communication and control functions carried out from control centers via neural-like functions. This architecture enables optimization of the power system according to environmental conditions and enables repaid adjustments to the buildup of stresses at the local and regional levels. It enables a rapid dissemination of signals and foster inter-site communications, limiting cascading effects and coordinates rapid responses to alterations in normal operation. Hopefully, it would promote load shedding and microgrid islanding in a way that prevents blackouts that extend over large regions of the future smart grid. These concepts will be discussed in more detail in the remainder of this section.

5.1 High-Level Control Architecture

In the control architecture depicted in Fig. 1, data and alerts are relayed to the control centers via the command module. This information stream (1) informs operators in the control center as to which set of MAS actions are taking place at any given time, and (2) alerts operators in the control centers that a situation has occurred that may require human intervention and repair activities. (3) In new facilities that allow for complete integration of the neural control unit, it may assume many of the duties of

Table 1 Operational security activities by multi-agent systems

Operational step	Agent Behavior	Reference
Substations		
Rapidly detect and respond	Defense	Li et al. (2005)
	Diagnostic support	Buse et al. (2003), Davidson et al. (2006)
	Secondary control	Wang et al. (2003)
Isolate local damage	Islanding, load shedding	M. Pipattanasomporn et al. (2009)
Restore normal operation	Power system restoration	Nagata and Sasaki (2002)
Microgrids		
Rapidly detect and respond	Primary control	Dimeas and Hatziargyriou (2005)
	Diagnostic support	J. Oyarzabal et al. (2005)
	Secondary control	Jimeno et al. (2011)

a firewall. In other, older facilities, it could provide an independent data stream from agents active in the substations and microgrids.

Listed in Table 1 is a partial list of agent behaviors that have been developed by the research groups listed in Column 3. These serve as exemplars of how these control modules would operate in practice at substations and microgrids. These have arranged according to which operational security step they support. In marrying MAS technologies with a neural control module, the basic idea adopted from biology is to provide for central control and coordination by the command module while leaving considerable local autonomy for the agents to cooperate with one another and act according to what they encounter locally. Non-local environmental information that is relevant to their duties is relayed to them in a timely manner via the neural command module. In this biological paradigm, control is spread across neuro-immune levels in a manner that enables each component to optimally contribute to the overall task of maintaining the *milieu intérieur*.

5.2 Substation Control

There are a large number of networked sensing devices and access points embedded within SCADA systems that can be exploited for cyber-attacks (Ericsson 2010; Wei et al. 2011) and should be monitored. These include, for example, protection relays, digital fault recorders (DFRs), LAN switches, remote terminal units (RTUs) and human-machine interfaces (HMIs). Cyber attacks may take one of several forms. They may, for example, be triggered by injection of false data into the substation data stream (Y. Liu et al. 2011) leading to erroneous actions by operators in control centers. The attacks may take a loss or denial of service form if equipment is either turned off or blocked, or alternatively, the attacks may generate physical damage to equipment (as exemplified by Stuxnet).

The first stage in responding to loss of power system homeostasis, whether it is due to supply/demand imbalances, component damage, or deliberate attack, is to detect the danger and launch an appropriate response. The time scales involved in achieving real-time responsiveness are quite short. Typical response times required within substations are on the order of 100 ms for fault disconnecting and on the order of 100 ms to 2 sec for automation control and monitoring (Ericsson 2010; Wei et al. 2011). A number of pioneering studies on how to achieve these challenging goals have been reported. For example, reference Li et al. (2005) addressed how to protect power system against malicious attacks, presenting a system that might be used to pinpoint dangerous situations in advance of a potentially catastrophic outage. Reference Buse et al. (2003) developed a multi-agent system that managed the large number of data acquisition, monitoring and control systems present in a substation, and reference Davidson et al. (2006) created a multi-agent system that provided diagnostic support and operated in conjunction with SCADA systems and fault recorders. Secondary control refers to maintenance of voltage and frequency stability between control areas. In reference Wang et al. (2003), a multi-agent system for secondary voltage control was explored. As noted earlier the transition from grid-connected to islanded operation is an important component of the smart grid. In reference M. Pipattanasomporn et al. (2009), the facilitation of this transition using MAS technologies was illustrated and reference Nagata and Sasaki (2002) introduced a set of bus agents plus a management agent that assisted in restoration of power in a local network.

5.3 Microgrid Control

An essential feature of the smart grid is the integration of distributed energy resources (DERs) into the low and medium voltage networks. Microgrids are an attractive model for aggregating and integrating some classes of DERs into the grid. They combine DERs such as micro-turbines, wind turbines, and fuel cells with energy storage devices (ESDs) such as batteries and fly-wheels. The DERs and ESDs are then jointly controlled and connected to the low voltage network in ways that enables them to operate in either grid-connected or islanded modes. In assessing the operational security requirements for these entities, it becomes clear that many of the same operational security and control capabilities as used in substations are required. In addition, the control system must handle not only islanding, load shedding and black startup but also market pricing (Dimeas and Hatziargyriou 2005; Lopes et al. 2006).

The utility of agents in operational security has been emphasized in several micro-grid studies (J. Oyarzabal et al. 2005; Jimeno et al. 2011). In reference J. Oyarzabal et al. (2005) the utility of agent systems to assume responsibilities carried out by SCADA and other control devices in substations was advanced, while reference Jimeno et al. (2011) explored secondary control applications. Given the increased security risks associated with microgrids, safe and secure integration into the main grid is a challenging task. Making upstream use of a neural command module and pattern generator similar to that advocated for use in substations could facilitate this activity.

6 Conclusion

In this chapter, we sketched how the smart grid of the future might not only guard against natural disasters and deliberate attacks, but also limit damage and promote recovery when these events do occur. The roadmap we presented was modeled on the innate immune system, a highly successful system of protection implemented across multiple phyla and kingdoms. As is the case for biological systems we included in the overall architecture central (neural) control that works alongside the distributed system of innate immune sensor/effector platforms.

With regard to this last point, biological organisms utilize a single, highly integrated immune/neural response and control system to deal with stresses, injury and invasion. The utilization of a single system for dealing with these seemingly different dangers is driven by the fact that many of the same operational response steps are involved in treating each of them. This commonality is strongly reflected by the use of the term sterile inflammation to describe inflammatory responses that occur in damaged tissue for which there is no sign of an invasion (Chen and Nuñez 2010).

The neuro-immune model of electric grid control presented in this chapter is both simplified and abstracted from its biological progenitor. This is done in part to relieve the structure of details tied to wet chemistry that are not relevant in engineering applications. Similarly, details can be expected to enter into developing smart grid descendent that are unique to the grid. One set of "details" may well carry over from biology to engineering is the danger of excessive responsiveness by macrophage/smart grid agents. This aspect was emphasized in this chapter, and several mechanisms to prevent this from happening were discussed.

A number of topics relevant to smart grid resiliency and self-healing were not discussed in this chapter. One of these is the best way to utilize the several means of communication available—optic fiber and the Internet, broadband over power lines (BPL), digital wireless, and microwaves. In biological systems, neural means are favored when rapid long-distance communication is required. In the smart grid, the availability of the aforementioned routes should help in the establishment of an effective analog to neural-like rapid communications.

It is just in the last few years that degeneracy has emerged as a means by which neural systems achieve robust performance. This striking finding is joined by earlier discovered ways CPGs simultaneously achieve stability to small perturbations and responsiveness to environmental changes. These biological properties are clearly desirable ones for the smart grid and will help it achieve resiliency and self-healing. These latter efforts are in their earliest stages, and a large amount of work remains to be done, especially in furthering cyber security against attacks from cyber criminals and agents of hostile nation-states.

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