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**A CONTROL ENGINEERING APPROACH TO  
MAKING COMPLEX INFRASTRUCTURES MORE  
EFFICIENT AND RELIABLE: A CORE PROGRAM  
FOR ESD**

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# **A Control Engineering Approach to Making Complex Infrastructures More Efficient and Reliable: A Core Program for ESD**

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## **1. Introduction**

Many of our national infrastructures, such as electric power, gas pipeline, transportation and information/communication systems suffer from common design, planning and operating problems. As a consequence of these problems, the infrastructures cannot function at the same time both efficiently and reliably. This presents a challenge of national importance that can be met within our own ESD Program.

In this paper, I present a research program using control engineering and systems theory as a unifying theme for modeling each infrastructure as a single complex dynamic system encompassing technical, economic, policy and information processes. Based on these models, the research program further seeks to develop controllers that force the infrastructure to operate both efficiently and reliably; the controllers respond to technical, economic and policy feedback. With these controllers in place, the design and planning of each infrastructure will naturally evolve to enhance efficiency and reliability. Since the controllers respond to any change in system conditions, they are equally as effective under malicious attacks. As such, they can function as a means of providing secure infrastructures.

The controllers I envision will operate naturally under regulated and deregulated policy conditions. Further, they can themselves evolve as policy conditions change so as to maintain reliable and efficient operation of the infrastructure. Moreover, they can catalyze policy evolution to support more reliable and efficient operation. Equally important, they will not just be traditional controllers that act on feedback signals to produce actuation signals. They will also be IT-based decision making tools that implement flexible information flow-based protocols between industry participants so as to support such activities as market operation and participant learning. Combining a systematic model-based approach to risk management with IT-intelligence and distributed hardware is a real opportunity to provide a framework for flexible dynamic robustness in complex systems. Neither IT nor control engineering by themselves are sufficient to embark on this tremendous challenge. One needs a very careful combination of the data mining techniques and the more structured control techniques to solve the problem.

In what follows, I will explain my vision for the ESD Program in the context of one infrastructure, namely the electric power system. This is the system on which most of my research has focused. Nonetheless, my vision for the program can extend to apply to the other infrastructures named above.

## **2. The Problems: Electric Power System Case Study**

The current design, planning and operating practices for electric power systems do not allow these systems to operate both reliably and efficiently. The systems are therefore either at risk of blacking out, or at risk of being too costly, or both. The problem is that in the traditional regulated industry there are no strong incentives for efficiency, so the tendency is to over-design, and be paid for cost plus guaranteed profit. In addition the design and operation of reliable electric power systems in the face of very low-probability, high-impact events are difficult. Consequently, it is fundamental that the electric power system cannot function efficiently due to the cost of providing the over-design of capacity required to achieve the regulated reliability. Despite the over-design one can still not guarantee reliability because of the difficulties with low-probability, high-impact events; these events will happen, but one can never design for all of them. Examples of such events are given in Section 3.

In contrast to the above, in the developing deregulated industry there is no value placed on reliability, so the tendency is to design and operate for efficiency at the expense of technical robustness. In this industry, no one is specifically penalized for blackouts, for example. Consequently, it is fundamental that the electric power system is at increased risk of blackout as economic pressures to transfer larger blocks of power over longer distances for profit stress the system. Despite the quest for efficiency and profit, one can still not guarantee efficiency because no one can yet model and influence economic dynamics. Examples of such modeling and control problems are given in Section 4. As we shall see in Section 5, I propose to treat the added capacity needed to provide reliability as a product with economic value. This value will feed back to the processes of planning and operation thereby guiding the system to higher reliability through economic incentive.

## **3. Background: Reliability Challenges**

As mentioned in the previous section, reliability is difficult to achieve because failures result from low-probability, high-impact events. Three types of these events are illustrated below.

The first type of event involves hidden failures in protective devices. For example, suppose a protective device, responding to a false alarm, disconnects the transmission line it is protecting. As a result, the remaining transmission lines are now overloaded, and their own protective devices now also disconnect. Ultimately, this leads to a cascading blackout. Several analyses of the early blackouts, as well as more recent analyses of brownouts and blackouts in California, show that each of these major problems started by a highly improbable event which was followed by a cascading disconnection of other pieces of major equipment, ultimately leading to system-wide disintegration and a widespread loss of service to end users.

A second type of event results from incomplete operating knowledge, such as the incomplete measurement of power exchanges. To illustrate this, consider a low probability loss of a power plant. In response, the system operator turns on another

power plant, assuming that distribution of power flow remains unchanged. In reality, the power flow distribution is much different. Because the operator is unaware of this difference, the system begins to overload and disintegrate. In the Northeast blackouts between 1960 and 1980, the power exchange with Canada was not directly monitored nor controlled. In the recent California blackouts, the power exchanges between California and the Northwest were also not directly monitored nor controlled. It is now understood that this lack of monitoring and control ultimately caused the blackouts; these blackouts were also exacerbated by hidden failures in protective devices.

A third type of event concerns malfunctioning of local distributed controllers that fail to recognize qualitatively different operating conditions from the ones for which they were tuned. Consequently they do not appropriately change their control logic. These types of events were responsible for blackouts in France, Belgium, South Africa and Italy several decades ago.

To achieve reliability in the face of the events described above requires more than a single approach. Hidden failures require protective devices smart enough not to respond to false alarms; they must double-check their own actions. Events resulting from incomplete power flow knowledge require extensive real-time power flow measurements and hierarchical controllers that act on this feedback. The problem of malfunctioning local controllers requires adaptive logic capable of recognizing qualitative changes of operating conditions. The development of these approaches poses open research problems in the area of control engineering for complex dynamical systems. Moreover, even if these problems could be solved in a deregulated power industry, there might not be incentive to adopt the solutions.

#### **4. Background: Efficiency Challenges**

Just as reliability is difficult to achieve even in regulated industries, so too efficiency is difficult to achieve even in deregulated industries. The reason being that our economy is a dynamic process and no one today can model it, much less control it. Further, if one begins to value such intangibles as reliability, the dynamics are yet more difficult to model. The practice today is to treat economic processes only in equilibrium. For example, a clearing mechanism for a typical short-term electricity market is based solely on top-down optimizations of static equilibria. To manage longer-term financial and/or physical risks, and thereby improve reliability, one needs longer-term incentives, which cannot be made in short-term electricity markets. Longer-term incentives play out over time periods long enough for the economy to be dynamic, and therefore to include reliability along with efficiency requires consideration of economic dynamics. Our ability to consider these dynamics is completely missing today.

Moreover, today there are major asymmetries between incentives given to power producers, marketers, consumers and delivery companies. Power producers and marketers alone are given incentives today. It is critical to introduce technologies and policies that make (groups of) consumers more responsive to system conditions. Also, in order to facilitate the penetration of technologies which are essential to make energy delivery efficient, one must move beyond guaranteed cost-plus-fixed-profit payment for transmission. Efficient performance-based regulation of complex networks in which

spatial and temporal processes are valued through transmission pricing, for example, is currently one of the major open problems in regulatory economics in several critical infrastructures, including electric power networks. Without this, it is difficult to have sustainable transmission technology. An even harder problem is to create longer-term transmission markets in which end users purchase transmission rights at value to hedge against real-time congestion uncertainties, and the pricing of the rights provides a basis for new investments into transmission technologies of greatest long-term value to the end users. (The Federal Energy Regulatory Commission is struggling with this now.) A peculiar issue here is that unless reliability-related risk management is valued as a separable service, it is almost impossible to differentiate between hedging against financial risks and the physical risks themselves.

In summary, it is clear that without meeting the economic, policy and IT challenges described above, one cannot hope for long-term efficiency under deregulation. As I describe in the following section, my vision is that control engineering and systems theory can be used to glue together the solutions both to these challenges and to technical challenges.

## **5. The Solutions: Electric Power Systems Case Study**

Outlined here is an approach to solving the design, planning and operating problems that plague electric power systems. The result is an infrastructure that functions both reliably and efficiently. The same approach is useful for protecting electric power systems under malicious attacks, i.e., making them secure. This approach is both a natural progression of my own research and my vision for a core ESD program. As argued below, my approach requires: (1) modeling of an electric power system as a single technical, economic and policy dynamic process, (2) advances in control engineering and systems theory to analyze the interdependencies of interest and to design near optimal feedback from the technical, economic and policy signals, in which optimality is measured in terms of efficiency and reliability, and (3) IT-based implementations of control algorithms operating on technical, economic and policy feedback to highly distributed and flexible sensors and actuators. Interestingly, this work must consider human decision makers as part of the system. I describe next how generalized systems theory, combined with IT and the specific modeling of critical infrastructures has the potential to become a backbone of a flexible robust electric power system.

### **5.1. Modeling for efficiency and reliability**

I propose here that a dynamic model for establishing the basic interdependencies between capacity (generation and/or transmission), its pricing and the underlying policy (regulation) is fundamental to introducing meaningful definitions of dynamic efficiency and reliability. The problem of efficient and reliable system performance can then be posed as a control problem with explicitly stated economic, policy and technical sub-objectives.

To establish a relevant model<sup>1</sup>, I start by deriving a single dynamic model of a complex electric power system, whose states, inputs, outputs, and disturbances are defined to encompass technical signals, and the corresponding economic (prices) and policy (type of regulation) signals. The current state-of-the-art of modeling the electric power system/industry is highly deficient since individual sub-processes are studied under strong assumptions about other sub-processes. For example, the operation and planning of the physical system are still largely carried out without considering the dynamic interplay of physical quantities with the pricing of these quantities. Even more troublesome are the poorly understood dynamic interactions between the policy state, on the one hand, and the technical and economic states, on the other hand; the consequences of this lack of understanding have been serious, as we have seen recently in California, and are likely to grow over time because of the overall complexity of the modeling problem.

The important concept is that the full coupling of the dynamics of the technical, economic, and policy states are now completely captured by a single dynamic model. These relations describe the dynamics of the technical states, economic states and policy states, representing conditions of the entire complex system and various feedback signals acting through controllers.

The technical states in the envisioned model are power injections, frequency, voltage, generation capacity, transmission capacity and the technology choice. The dynamics of the technical variables are functions of themselves, as well as functions of the economic and policy states. For a given policy, these functions follow from both basic engineering laws and basic economic laws. For example, the dynamics of scheduled power quantities will depend on the available capacity, the cost of the quantities themselves and technologies, and also on the market prices and the current policy state. The dynamics of frequency and voltage are slightly more involved to derive, but the principle is similar. Possibly the most relevant technical states for modeling efficiency and reliability are physical capacities, both generation and transmission. Their dynamics are also functions of themselves, as well as of scheduled power, capacity prices and the policy state.

The economic states are power prices, prices for frequency and voltage control (quality of service) and capacity prices, both generation and transmission. The dynamics of these variables are dependent on the variables themselves, and also on the physical variables and the state of policy. These dynamics follow from the basic laws of economics.

Finally, just as for the technical and economic states, the policy states must be represented as a vector, rather than a single state. Considering a sufficient number of policy states is essential for capturing the various hidden interactions within complex electric power system dynamics. In addition to the basic policy states such as the type of regulation (ranging from full regulation through full deregulation via many transitional forms), one needs policy states for major externalities, such as a policy state defining the delivery, reliability and environmental aspects of the system. The next policy state is

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<sup>1</sup> An appendix to this paper outlining the model can be provided.

generally dependent on the previous policy state, economic and technical states, and also, on factors which are not fully controllable, such as ideologies, human dissatisfaction and various political forces.

It is important to appreciate the degree of complexity of the model described here. The complexity is two-fold; it is both temporal and spatial. The temporal complexity is reflected in the dynamics of states varying at vastly different rates, resulting in complex hybrid dynamics in which changes in some states are inherently discrete in nature, and the others are continuous. It is wrong to separate these states a priori into slow and fast states, without careful analysis of the full model. It is easy, for example, to show counter examples to the commonly made claim that the economic processes are slower than technical processes, and faster than policy processes. While policy is rarely thought of as a dynamic process in its own right, its dynamics are very interesting, since it takes a long time for the policy to change, but when it begins changing it moves very fast. Rather than decoupling a priori the single technical-economic-policy process into sub-processes, one must study the conditions under which decoupling is valid. More importantly, one must derive reduced-order models by accounting for the effects of the other states in a systematic way. In the next section, I identify the major advances of the state-of-the-art model reduction in control engineering needed to systematically reduce the coupled technical, economic and policy model of a complex electric power system. As with any other model reduction problems, classes of reduced order models will be needed to study relevant interdependencies of interest.

The spatial complexity is also enormous. To begin with, the physical layer of the electric power system has a vast number of power producers and users, and these are interconnected via complex delivery networks, transmission networks for backbone power delivery and distribution networks for local delivery. Interacting with the physical layer is the complex architecture representing economic interactions among various markets and the market participants. The architecture of the regulatory (policy) layer also has distributed interactions within itself (federal and state) as well as with the economic and technical layers. It is unfortunately impossible to study efficiency and reliability in depth by blindly using pre-chosen aggregate models. Model aggregation, or reduction, must be carried out with great care so as not to lose dominant effects. Because my proposal for implementing reliable and efficient energy service is based on the principle of many small actors contributing in a flexible way to system-wide performance, one must aggregate micro-scale dynamics to describe macro-scale dynamic performance. In Section 5.2, I describe the problem of model reduction to minimize spatial and/or temporal complexity in a systematic way as one of the prime challenges to the state-of-the-art model reduction and aggregation techniques in large-scale dynamic systems.

In summary, the system development of reliable and efficient electric power systems requires modeling and an understanding of their dynamics. We have already had examples of serious problems because such systematic developments have never been carried out. For example, the California energy crisis exposed major interdependencies between the quantities and prices of scheduled power, the capacity additions and the environmental policy. Most interestingly, this crisis evolved through dynamic interactions over fairly long-time horizons. To model, analyze and ultimately prevent some of these problems through generalized feedback design in response to economic,

technical and/or policy states, a library of models, systematically aggregated over time and space, must be developed in support of software-based tools capable of extracting the interplay of interest.

## **5.2. Necessary Advances in Systems Theory and Control Engineering**

I view electric power system robustness as the ability to minimize the effects of very low-probability, high-impact triggering events on the system-wide performance. It is plausible that some of these triggering events could be hidden, as in several blackout cases, initiated either by a false alarm of a protective device, or by the incorrect logic of a local controller. The impact of these hidden events is typically characterized by a sequence of cascading failures, ultimately resulting in the collapse of major system portions requiring complex and costly restorations.

How successful the power industry and society are when attempting to prevent such high-impact cascading events greatly depends on the joint state of policy, economic incentives and technological solutions. I propose to use control engineering and systems theory approaches to develop meaningful models for analyzing and designing different policy, economic and technical means to ensure robustness in the least conservative way possible. These theories provide a systematic and rigorous framework for modeling dynamic interdependencies within and among various layers of the system and for systematic control design.

To pursue this path, we will need major advances in control engineering and systems theory. For example, it is well known that robustness could be studied using a control engineering approach, and, more broadly, systems theory. Unfortunately, it is also well known that these top-down robust control design techniques are highly conservative, and so essentially not very useful for large-scale complex dynamic systems. A better approach is to first apply temporal and spatial aggregation to the large-scale dynamic model of the power system, and then develop robustness based on these simpler models. This leads to a mind-twisting adaptive model reduction of a very heterogeneous hybrid model.

A complete control design and decision making problem involves a set of objectives determined by (1) engineers defining the technical objectives; (2) policy makers defining industry objectives; and (3) economists defining pricing objectives within the industry structure determined by the policy makers. These objectives are coupled through a single complex dynamic model. As mentioned earlier in Section 5.1, one cannot assume a priori that the relative rates at which technical, economic and policy states interact permit this model to split into three separate independent models. Therefore, the problem as posed is too complex to solve even for its equilibrium conditions. Rather, it is necessary to develop a separate reduced-order model to support design of a separate controller to meet each of the three objectives. Each reduced-order model will retain the technical, economic and policy dynamics relevant to achieving the corresponding objectives. In this way, the control of the electric power system can be simplified to the development of three smaller controllers.

Depending on the initial conditions of the entire state (policy, economics and technical variables), the architecture of the system should evolve over time to become more reliable and efficient if the policy objectives contain explicit measures of reliability and

efficiency. These measures must also be fed back to the people who design economic (pricing) and technical controllers. In turn, the results of technical decisions and economic decisions will ultimately affect changes in policy states toward a more favorable policy in support of reliable and efficient electric power systems. It is extremely important to understand that, under my approach, the system hierarchies evolve dynamically into different layers which are most favorable for achieving the original objectives, and that these are shaped by a variety of technical, economic and policy decisions.

### **5.2.1. Toward an Optimal Policy for More Efficient and More Reliable Electric Power Systems**

An optimal policy must provide incentives for the efficient use of existing capacity and for new capacity investments. I have proposed in my work that to achieve this one must have a policy which defines reliability as an explicit product. This sets the basis for its economic valuation and therefore gives incentives to technology to support flexible management of capacity over time. How such a near-optimal policy state would envision differentiated reliability service greatly depends on many societal and political criteria. For example, some societies view electricity service as a basic right, and in this case there will be need for subsidies of various kinds to those who cannot afford to pay for high-quality electricity service. On the other hand, one must give some incentives to those willing to get interrupted when the system is under stress and pay less for this service. Consequently, I plan to further develop models and policy objectives and to design optimal policy control capable of inducing this performance. Development of the right policy (or classes of policy) is critically important in order to catalyze penetration of extremely valuable technologies (software and hardware) which naturally lend themselves to this concept.

In sharp contrast with the old regulated and current transitional industries where the technological challenges are huge, particularly the control-related hurdles summarized above, implementing value-based distributed management of more reliable and more efficient systems is much more straightforward. The new technologies that will shape the very structure of the industry are already here. Many of these technologies are disruptive to the current practices. The most profound and disruptive change concerns small distributed power plants replacing large-scale power plants. Many other new technologies supporting much more active participation of the electricity users (ranging from long-available set-back thermostats through automatically balanced demand and adjustable speed-motors, all supported by various metering and switching devices) are also disruptive. Some users may desire to have a choice of more environmentally sustainable power than currently provided by the existing plants. Others may prefer lower cost, or greater control over power availability, or the potential for lowering payout by selling cheaply-generated solar or wind power back into the grid. Similarly, transmission and distributions will involve vast arrays of controllable switches to implement flexibility, many of these being located closer to the users. More localized storage of energy, particularly of locally-generated solar or wind power, also appears likely. Such storage will have the fundamental value of enabling the users to acquire energy at a lower price, for use when it is more expensive. With more effective, lower cost devices, storage could become routine, and potentially widely distributed. IT has a clear potential for changing use patterns.

A future decentralized system is clearly based on the homeostatic control conceived some time ago by the late Fred Schweppe, but the basic concept needs tremendous extensions. Such systems could provide coordination through information requirements—any device attached to the power grid might be required to “announce” itself and its characteristics (how much power it uses or might generate, for example.) In any event, regulations will be needed to assure that the necessary information is provided to coordinate the system, preferably in some automated, non-intrusive way.

In summary, I find that there has not been much modeling of the dynamics of economic and policy processes, their interactions and the interactions with technologies in very large complex systems, such as electric power systems. I suggest that this is possible and I describe in the following section how IT has changed our ability to identify models and tune their characteristics in an on-line environment to account for various nonlinear effects and behavioral aspects, including gaming, market power, etc. In this age of unlimited IT data mining which is beginning to make a big difference, it is time to establish models that include dynamic strategies for policies and pricing. These models are needed to design methods for short-term and long-run robustness of complex infrastructures over differing time horizons.

### **5.3. IT for More Efficient and More Reliable Electric Power Systems**

Major advances in small-scale distributed sensors, actuators and IT will make distributed intelligence a reality by developing data-based models, by verifying these models and updating them in an on-line setting. The early concepts from generalized systems theory for self-organizing and flexibility and the more recent concepts from computer science on distributed learning for control and multi-agent decision making must be combined to achieve highly distributed flexible management for robustness. This is a qualitative departure from the static coordination and conservative design for robustness in all major older infrastructures. I see combining systematic model-based approaches to managing risk in a complex system with various IT intelligence and distributed hardware options as a real opportunity to provide a framework for flexible dynamic robustness in complex systems.

Also, the software-based methods needed to induce system evolution from the current state into a highly decentralized state involving active end users are far behind what is needed and what is possible. Markets, users and groups can be re-aggregated and reconfigured “virtually”, via IT, depending on the patterns of use or demand, and depending on the quality defined in terms of characteristics such as reliability, non-interruptibility, and amount of power, among others. Given multiple sources for power and multiple dynamically re-configurable markets, a viable new industry structure might center on brokers who “wheel and deal”, owning no assets for generation or transmission themselves, but servicing the IT/reconfigured demand. Such brokers are already present in the industry under transition, but often with poorly defined market rules, particularly in relation to the reliability risks. This is an example of how technology would affect change of policy state.

IT also affects electric power system dynamics because information is not perfect, and the information asymmetries are valuable. The ability to use information is not homogeneous and the ability to change or reconfigure in response to demand shifts is also valuable. Inter-temporal information and asymmetry translate to non-coincidental

peaks, thus the use of information can substitute for capacity, convenience, demand and time.

The impact of IT on the system structure as a whole can scarcely be overstated. Indeed, real-time information offers the single most powerful response capability to adjust to system evolution much more so than seeking to forecast a complex nonlinear system. By operating on fact and rapidly readjusting, rather than operating on forecasts that might be wrong, dynamic IT-enabled system response will surely diminish its vulnerability and transform the system into a highly flexible responsive mechanism.

The IT-based control engineering for complex infrastructures is potentially very straightforward. It naturally lends itself to homeostatic control, swarm intelligence and multi-agent reinforcement learning and the like. Dynamic, or virtual, aggregation of many small decision makers to extract the remaining benefits from the economies of scales is a very important challenge. Here, in particular, I see a real opportunity to enhance the use of the interaction variables I introduced for dynamic aggregation of the complex system into different layers as these get formed in response to policy, economic and technological feedback. Portfolio building by the suppliers or coalitions of consumers becomes a very important mechanism for adjusting the size of decision makers to the technology of interest and its value to the group as a whole. The interdependence of portfolio and coalitions building dynamics and the policy state feedback needs major study.

## **6. Summary**

In summary, I propose a novel and visionary program for ESD that will develop a more efficient, reliable and secure electric power infrastructure. Further, I believe that the research to be carried out under this program is directly applicable to the improvement of other critical national infrastructures. Given the opportunity, I would work with the experts from other infrastructures to develop corresponding programs within ESD.

I have described here only the research component of my vision. If desired, I could also share my thoughts on education, which include developing new courses and a major control laboratory for simulating and testing controllers for complex infrastructure systems. I could explain how the existing courses I have introduced for electric power systems (6.686, 6.689 and 6.683/112J) fit this vision and could identify the next steps.

This program, encompassing both education and research on complex infrastructure systems, could serve as a role model for all such programs at major universities.