CHAPTER 1

# A FRAMEWORK FOR INTERDISCIPLINARY RESEARCH AND EDUCATION

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## 1.1 INTRODUCTION

Electric Power Networks Efficiency and Security (EPNES) deals with fundamental issues of understanding the security, efficiency and behavior of large electric power systems, including utility and United States Navy power system topologies, under varying disruptive or catastrophic events. A robust power system is to be measured in terms of various attributes such as survivability, security, efficiency, sustainability, and affordability.

There is an urgent need for the development of innovative methods and conceptual frameworks for analysis, planning, and operation of complex, efficient, and secure electric power networks. If this need is to be met and sustained in the long run, appropriate educational resources must be developed and available to teach those who will design, develop, and operate those networks. Hence, educational pedagogy and curricula improvement must be a natural part of this endeavor. The next generation of high-performance dynamic and adaptive nonlinear networks, of which power systems are an application, will be designed and upgraded with the interdisciplinary knowledge required to achieve improved survivability, security, reliability, reconfigurability and efficiency.

Additionally, in order to increase interest in power engineering education and to address workforce issues in the deregulated power industry, it is necessary to develop an interdisciplinary research-based curriculum that prepares engineers, economists, and scientists to plan and operate power networks. To accomplish this goal, it must be recognized that these networks are socio-technical systems, meaning that successful functioning depends as much on social factors as on technical characteristics. Robust power networks are a critical component of larger efforts to achieve sustainable economic growth on a global scale.

*Economic Market Design and Planning for Electric Power Systems*, Edited by James Momoh and Lamine Mili

The continued security of electric power networks can be compromised not only by technical breakdowns, but also by deliberate sabotage, misguided economic incentives, regulatory difficulties, the shortage of energy production and transmission facilities, and the lack of appropriately trained engineers, scientists and operations personnel.

Addressing these issues requires an interdisciplinary approach that brings together researchers from engineering, environmental and social-economic sciences. NSF anticipates that the research activities funded by this program will increase the likelihood that electric power will be available throughout the United States at all times, at reasonable prices, and with minimal deleterious environmental impacts. It is hoped that a convergence of socio-economic principles with new system theories and computational methods for systems analysis will lead to development of a more efficient, robust, and secure distributed network system. Figure 1.1 depicts the unification of knowledge through research and education.

Research is needed to develop the power system automation technology that meets all of the technical, economic and environmental constraints. Research in the individual disciplines has been performed without the unification of the overall research theme across boundaries. This may be due to lack of unifying educational pedagogy and collaborative problem solving among domain experts, both of which could provide deeper understating of power systems under different conditions.

In order to overcome the existing barriers between intellectual disciplines relevant to development of efficient and secure power networks, innovative and integrated curricula and pedagogy must be developed that incorporates advanced systems theory, economics, environmental science, policy and technical issues. These new curriculum will motivate both students and faculty to think in a multidisciplinary manner, in order to better prepare the workforce for the power industry of the future. The EPNES solicitation therefore embraces a multidisciplinary approach in both proposed research and education activities. Some potential cross

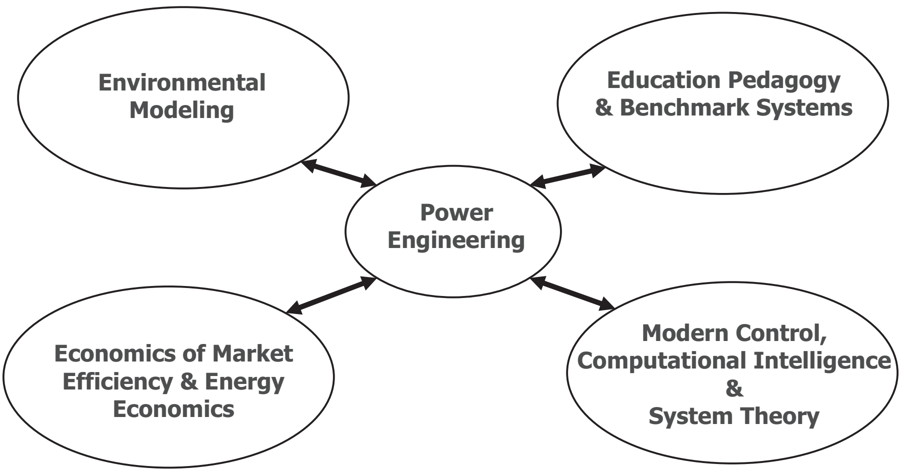


Figure 1.1. Unification of knowledge through research and education.

cutting courses are Financial Engineering, Power Market and Cost Benefit Analysis and Power Environment, Advances System Theory and Computational Intelligence, Power Economics, and Computational Tools for Deregulated Power Industry.

We recommend that all multidisciplinary courses use canonical benchmark systems for verification/validation of developed theories and tools. When possible, the courses should be co–taught by professors across disciplines. To promote broader dissemination of knowledge and understanding, courses should be developed for both undergraduate and graduate students. These courses should also be made available through workshops and lectures, electronically, and should be posted on the host institution website. Furthermore, an assessment strategy should be developed and applied on an ongoing basis to ensure sustainability of the program and its impact on attracting students and improving workforce competencies in promoting or developing an efficient and reliable power systems enterprise.

## 1.2 POWER SYSTEM CHALLENGES

The EPNES initiative is designed to engender major advances in the integration of new concepts in control, modeling, component technology, and social and economic theories for electrical power networks' efficiency and security. It challenges educators and scientists to develop new interdisciplinary research-based curricula and pedagogy that will motivate students' learning and increase their retention across affected disciplines. As such, interdisciplinary research teams of engineers, scientists, social scientists, economists, and environmental experts are required to collaborate on the grand challenges. These challenges include but are not limited to the following categories.

***A. Systems and Security***

- Advanced Systems Theory: Advanced theories and computer-aided modeling tools to support and validate complex modeling and simulation, advanced adaptive control theory, and intelligent-distributed learning agents with relevant controls for optimal handling of systems complexity and uncertainty.
- Robust Systems Architectures and Configurations: Advanced analytical methods and tools for optimizing and testing configurations of functional elements/architectures to include control of power electronics and systems components, complexity analysis, time-domain simulation, dynamic priority load shedding for survivability, and gaming strategies under uncertainties.
- Security and High-Confidence Systems Architecture: New techniques and innovative tools for fault-tolerant and self-healing networks, situational awareness, smart sensors, and analysis of structural changes. Applications include adaptive control algorithms, systems and component security, and damage control systems for continuity of service during major disruptions.

***B. Economics, Efficiency and Behavior***

- Regulatory Constraints and Incentives: New research ideas that explore the influence of regulations on the economics of electric networks.

- Risk Assessment, Risk Perceptions, and Risk Management: Novel methods and applications for linking technical risk assessments, public risk perceptions, and risk management decisions.
- Public Perceptions, Consumer Behavior, and Public Information: Innovative approaches that improve public perception of electric power systems through increased publicity and education about the electric power networks.

**C. *Environmental Issues***

- Environmental Systems and Control: Innovative environmental sensing techniques for system operation and maintenance, improvements in emission control technologies, and/or network operation for minimization of environmental impact, among others. The interplay of these factors with the other topics in this solicitation is a requirement.
- Technology for Global Sustainability: Cross-disciplinary efforts that contribute to resource and environmental transitions that are needed to ensure long-term sustainability of global economic growth.

**D. *New Curricula and Pedagogy***

- New Curricula and Pedagogy: Innovative and integrated curricula and pedagogy incorporating advanced system theory, economics, and other social science perspectives, as well as environmental science, policy, and technical issues are desirable. New and innovative curricula to raise interest levels of both students and faculty, and better prepare the workforce for the power industry of the future are also desirable. Pedagogy and curricula must be developed at both the undergraduate and graduate students' level.

**E. *Benchmark Test Systems***

- Benchmark Test Systems: These are required for validation of models, advanced theories, algorithms, numerical and computational efficiency, distributed learning agents, robust situational awareness for hierarchical and/or decentralized systems, adaptive controls, self-healing networks, and continuity of service despite faults. A Navy power systems baseline ship architecture is available at the United States Naval Academy, website, http://www.usna.edu/EPNES.
- Both civil and Navy test beds will be available from the Howard University website: http://www.cesac.howard.edu/.

### 1.2.1 The Power System Modeling and Computational Challenge

Today, power system architectures are being made more complex as they are enhanced with new grid technology or new devices such as Flexible AC Transmission System devices (FACTS), Distributed Generation (DG), Automatic Voltage Regulator (AVR), and advanced control systems. The introduction of these systems will affect overall network performance. Performance assessments to be done can be of two types, either static and dynamic, or quasi-static dynamic behaviors under different (N-1) and (N-2) contingencies.

Several methods are commonly used for evaluating the performance of power systems under different conditions. For small and large disturbances, the methods include Lyapunov stability analysis, Power flow, Bode plots, reliability stability assessment and other frequency response techniques. These tools allow us to determine the various capabilities of the power system in an online or offline mode.

The tools will enable us to achieve better performance analyses, even taking into account other interconnecting networks on the power systems. These can include wireless communication devices, distributed generation and control devices such as generation schedulers, phase shifters, tap changing transformers, and FACTS devices. In addition to new modeling techniques that incorporate uncertainties, advanced simulation tools are needed.

### 1.2.2 Modeling and Computational Techniques

Develop techniques that consider all canonical devices, as well as new devices and technologies for power systems, such as FACTS and Distributed Generation, transformer taps, phase shifters with generation, load, transmission lines, DC/AC converters and their optimal location within the power system. The development of new load flow programs for DC/AC systems for ship and utility systems that take into consideration the peculiarities of both systems is desirable.

### 1.2.3 New Curriculum that Incorporates the Disciplines of Systems Theory, Economic and Environmental Science for the Electric Power Network

EPNES supports research that is performed in interdisciplinary groups with the objective of generating new concepts and approaches stimulated by the interaction of diverse disciplines. This will foster the development of pedagogy and education material for undergraduate and graduate level students. The initiative supports education, outreach and curriculum improvements to most effectively educate the future workforce via an interdisciplinary research approach of significant intellectual merit and broader impacts to the country as well as the global scientific community.

## 1.3 SOLUTION OF THE EPNES ARCHITECTURE

The explanation of the interaction of different phases of the EPNES framework is presented in terms of sustainability, survivability, efficiency and behavior. It satisfies the economic, technical and environmental constraints and other social risk factors under different contingencies. It is modeled using advanced systems concepts and accommodates new technology and testable data using the utility and military systems.

### 1.3.1 Modular Description of the EPNES Architecture

*Module 1: High Performance Electric Power systems (HPEPs)*
This is the ultimate automated power systems architecture to be built with the attributes of survivability, security, affordability, and sustainability. The tools developed in the modules below are needed to achieve the proposed HPEPs.

*Module 2: Mathematical Analysis Toolkit*

This module is dedicated to providing models of devices using the elements of advanced system theory and concepts, intelligent distributed learning agents and controls for optimal handling of systems complexity, robust architectures and reconfiguration, and secure, high confidence systems architecture. The toolkit will require development of new techniques and innovative tools for the optimization and testing of functional elements for electronics and systems components, complexity analysis, time domain simulation, dynamic priority load shedding for survivability, and gaming strategies under uncertainties. Additionally, for secured and high confidence systems architectures, these tools develop new techniques and analysis techniques for self-healing networks, situational awareness, smart sensors, and structural changes. This toolkit will also utilize adaptive controls, component security and damage control systems for continuity of service during major disruptions.

*Module 3: Behavior and Market Model Tool*

This module is to be designed based on the design parameters and cost data from the mathematical analysis tool, in order to define the economic and public perception for HPEPS. The module computes regulatory constraints and incentives that economically influence the operation of electric networks. The module provides innovative methods for linking risk assessments, public perceptions and risk management decisions. The computation of risk indices based on uncertainties and adequate pricing mechanisms is performed in this module. The computation of cost benefit analysis of different strategies is also to be included.

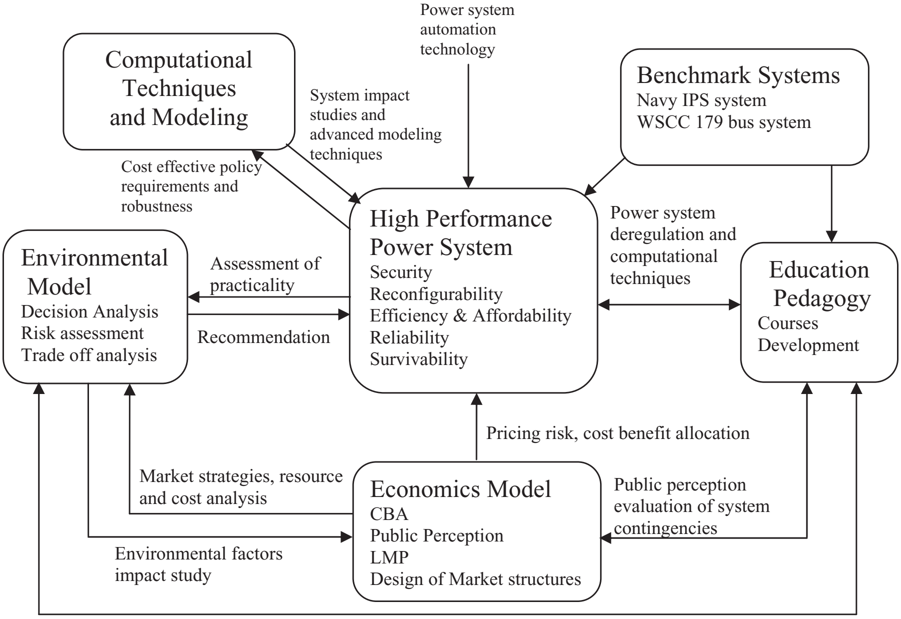


Figure 1.2. Modular representation of the EPNES framework.

*Module 4: Environment Issues and Control*
This module utilizes innovative environmental sensing techniques for system operation and maintenance. Improvements in emission controls techniques for minimization of environmental impact are required. To achieve this objective, several indices are needed to compute the environmental constraints that will be included in the global optimization for developing the risk assessment and cost-benefit analysis tools. The trade-off computed in this module will be used to determine new input for optimizing the HPEPS.

*Module 5: Benchmark Test System*
The validation of the models, advanced algorithms, numerical methods and computational efficiency will be done using the tools developed in the previous modules using the benchmark systems. Representative test beds and some useful associated models will be described in a later section of the paper. Different performance parameters or attributes of the HPEPS will be analyzed using appropriate models based on hierarchical and decentralized control systems, to ensure continuity of service and abilities in the design and operation of the proposed power system.

### 1.3.2 Some Expectations of Studies Using EPNES Benchmark Test Beds

Two test beds, involving civilian and military ship power systems, are proposed to support the evaluation of the performance, behavior, efficiency and security of the power systems as designed. The first is a representative civilian utility system which can be a US utility system, or the EPRI/WSCC 180 bus system. Also, the US Navy benchmark Integrated Power System (IPS) system designed by Professor Edwin Zivi of the US Navy Academy is a representative Navy testbed example. Both systems consist of generator models, transmission networks and interties, various types of loads and controls and new technology such as FACTs, AC/DC transmission, distributed generation and other control devices. To ensure that all of the elements of EPNES are considered by the researchers, including the issues of environmental constraints (such as emission from generators, plants or other devices), public perception, and pricing and cost parameters for economic and end-risk assessment.

Stemming from studies done on the benchmark systems, we plan to assess the security and reliability of the systems in different scenarios. For the economics studies, we plan to assess the cost benefit analysis acquisition tradeoff (cost versus security) and also determine the optimum market structures that will enhance the efficiency of the power system production and delivery. We plan to evaluate the risk assessment and public perception of different operational planning scenarios, given the environmental constraints. The 'why' and 'how' of the analysis of multiple objectives and constraints will be analyzed/visualized using the advanced optimization techniques. We also expect that researchers will take advantage of distributed controls and hierarchical structures to handle the challenges of designing the best automation scheme for future power systems that will adapt itself to different situations, reconfigure itself, sustain faults and still remain reliable and affordable.

## 1.4 IMPLEMENTATION STRATEGIES FOR EPNES

### 1.4.1 Performance Measures

To design reliable and secure power systems of the future, a multi-function performance metric is needed. In EPNES, we want the development of tools for measuring reliability, stability and security, affordability, sustainability and behavior of the power system under duress while taking into account environmental issues, public perception, and social impacts. Below is a summary of some of the key objectives in the EPNES framework.

### 1.4.2 Definition of Objectives

1. Survivability, in general terms, can be defined as the ability of a system, subsystem, or hardware component to withstand the effects of harsh disturbances, adverse environmental conditions, and/or structurally damaging natural or man-made effects. The goal of enhancing survivability is to reduce technical and human risks, while maintaining primary operational coordination, communication, and control functions during contingencies, as well as maintaining system structural integrity for autonomous healing with minimum disruptions. Thus, enhancing survivability is an indirect approach to improved risk levels for operation of the network under anomalies of loadings, man-made attacks, outages, cascading ruptures, effects of nature, and other source of disturbances.
2. Affordability is the process of minimizing system costs subject to the cost constraints associated with all needed components and services of associated resources. In the framework of this work, the costs associated with a high performance power system include installation of infrastructure, fuel and energy requirements, damage control in post fault scenarios, as well as the costs associated with implementing new or old control measures. Affordability is used to meet a setpoint performance requirement at a sufficient level of quality service (an aspect of public perception) and response of a service in need, when needed and regardless of the price (demand-supply balance). Who is willing to pay? To answer this question, research is needed to model and evaluate public perception and social impacts of decisions.
3. Efficiency of electric power networks has technical and market-driven economic components. This includes the cost of ancillary services that are required to sustain the operation of the power network. Efficiency is often seen as a performance measure of cost minimization subject to the constraints of fuel prices, value-added bidding strategies for competing resources, and effective use of resources in normal operation as well as during system faulted conditions. The cost minimization process should be extended to include the constraints on the environment in the economic model of the network.

4. Sustainability is an index that provides insight as to how well the system can maintain a relatively safe and economical margin of reliability, grid/network integrity, and system capability to function under conditions of shock, isolation, or heavy loading. In the short term, robust power network controls should provide suitable levels of stability and reliability to prevent localized brown-outs/black-outs, cascading failures, or system-wide interruption of service. This is true in the long term but requires emphasis on economic and environmental constraints in a competing market of scarce resources.

### 1.4.3 Selected Objective Functions and Pictorial Illustrations

This section broadly specifies the nature of the objective functions for survivability, affordability, efficiency, and sustainability of the electric power network. Accurate models for the various performance indices as well as market dynamics are needed. Overall, these objectives and several others will form the backbone of a comprehensive computational tool that will be used to solve the new breed of electric power networks operating under various conditions. The mathematical models for the selected objectives are summarized below.

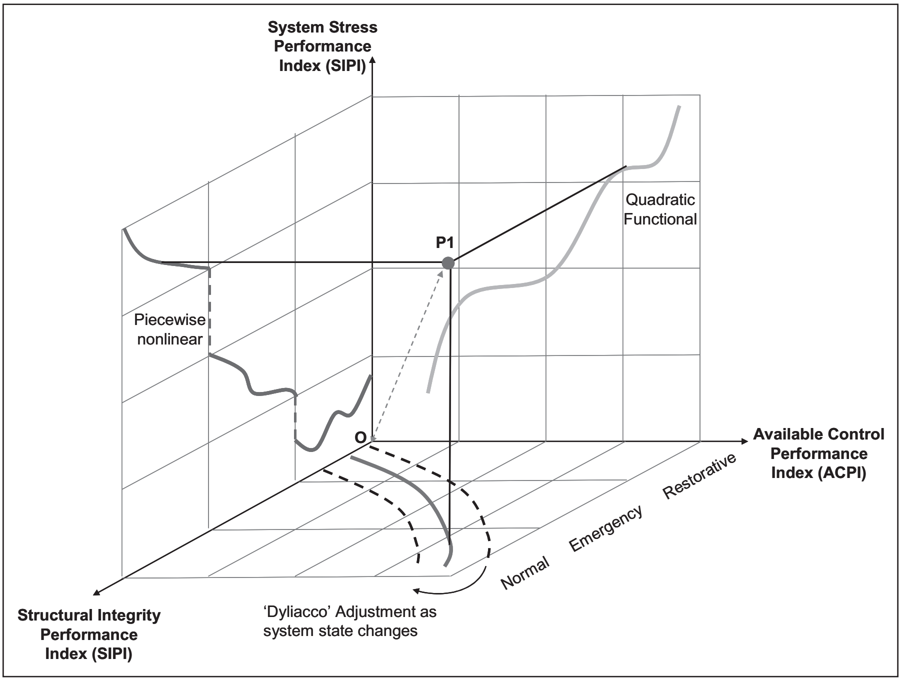


Figure 1.3. Sketch of the survivability objective function.

***1.4.3.1 Survivability Objective*** This objective characterizes the ability of the system or sub-system to be operated with minimum disruption using available controls to maintain structural integrity of the stressed network. The objective function (depicted in Figure 1.3) may be stated as:

$$\text{Minimize} \qquad F_{SV} = \sum_{t=0}^{T}\sum_{i=1}^{NS}\left\{\omega^T (k_{SS,i} SSPI_i(t) + k_{SI,i} SIPI_i(t) + k_{AS,i} ASPI_i(t))\right\}$$

*where:*

$SSPI_i(t)$ : System Stress Performance Index
$SIPI_i(t)$ : Structural Integrity Performance Index
$ACPI_i(t)$ : Available Control performance Index
$\omega^T$ : Weightings or correction vector for the respective indices
$k_{j,i}$ : Normalizing or model approximation for $j \in \{SS, SI, AC\}$
$t \in \{0, T\}$ : Time frame
$i \in \{1, NS\}$ : Set of subsystems in the network

***1.4.3.2 Affordability Objective*** This objective attempts to minimize the cost of operating the network subject to the budgetary considerations. The objective function (depicted in Figure 1.4) may be stated as:

$$\text{Minimize} \qquad F_{AF} = \left|\sum_{t=0}^{T}\left\{\sum_{i=1}^{NS} a_i^T (C_{CM,i}(t) + C_{FS,i}(t) + C_{TI,i}(t)) - \mu^T(t)\hat{F}_{SB}(t)\right\}\right|$$

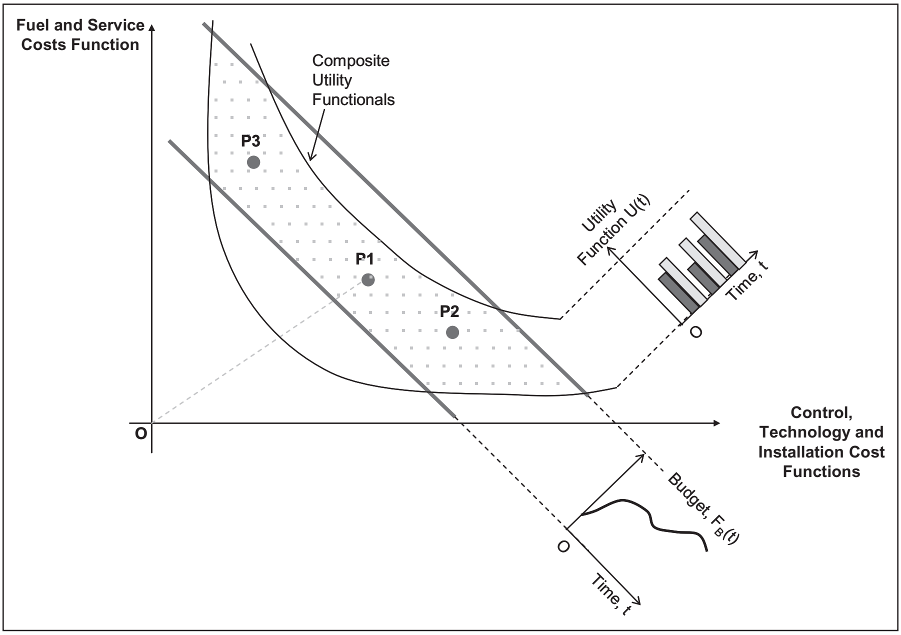


Figure 1.4. Sketch of the affordability objective function.

*where:*

$C_{CM,i}$ : Control and Maintenance costs
$C_{FS,i}$ : Fuel and Service costs
$C_{TI,i}$ : New Technology and Installation costs
$a_i^T$ : vector of weights and correction multipliers
$\mu^T$ : Willingness-to-Pay Penalty functions
$i \in \{1, NS\}$ : Set of subsystems in the network
$t \in \{0, T\}$ : Time frame

***1.4.3.3 Efficiency Objective*** This objective characterizes the cost-effective usage of energy, control, and ancillary support services in the electric power networks and as such, it has technical and market-driven economic components. The objective function (depicted in Figure 1.5) may be stated as:

$$\text{Minimize} \qquad F_{AE} = \sum_{t=0}^{T}\sum_{i=1}^{NS}\left\{\frac{\Delta_i^T}{\omega_{C_i}}(C_{AS,i}+C_{FC,i}+C_{AC,i})(t) - \left(\Delta_i^T \lambda_i^T f_{\substack{budget \\ \text{constraint}}}\right)(t)\right\}$$

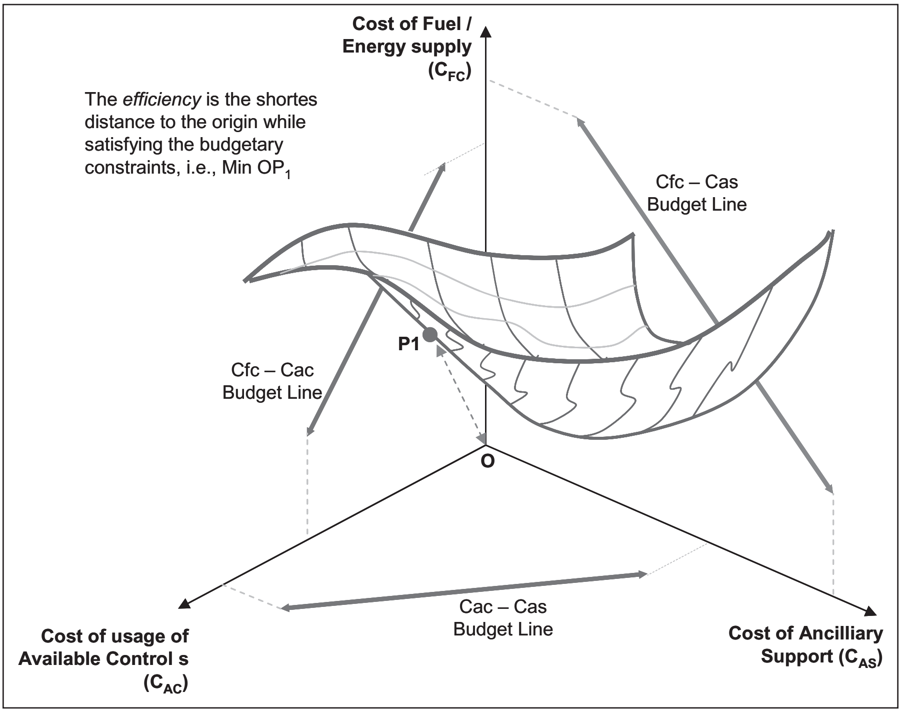


Figure 1.5. Sketch of the efficiency objective function.

*where:*

$C_{AS,i}$ : Cost of Ancillary Service support
$C_{FC,i}$ : Cost of Fuel / Energy
$C_{AC,i}$ : Cost of Usage of Available Control options
$\Delta_i^T$ : Past and Present time span, [*t, t-1*]
$\omega_{C_i}$ : Scaling multipliers
$\lambda_i^T$ : Penalty functions
$f_{\substack{budget\\ \text{constraint}}}$ : Budgetary constraints
$i \in \{1, NS\}$ : Set of subsystems in the network
$t \in \{0, T\}$ : Time frame

***1.4.3.3 Sustainability Objective*** Sustainability, loosely stated as 'minimizing intervention,' is an objective that measures network capability relative to safe and economical margins of reliability, grid/network integrity, and system capability to function under conditions of shock, isolation, or heavy loading. The objective function (depicted in Figure 1.6) may be stated as:

$$\text{Minimize } F_{SU} = \sum_{t=0}^{T}\sum_{i=1}^{NS}\{k_1[\beta_{rel,i}(1 - I_{rel,i}(t)) + \beta_{sta,i}(1 - I_{sta,i}(t))]\} + \sum_{t=0}^{T}\sum_{i=1}^{NS} k_2\left(CBS_{oper,i} + \mu_i^T h_{econ}(t)\right)$$

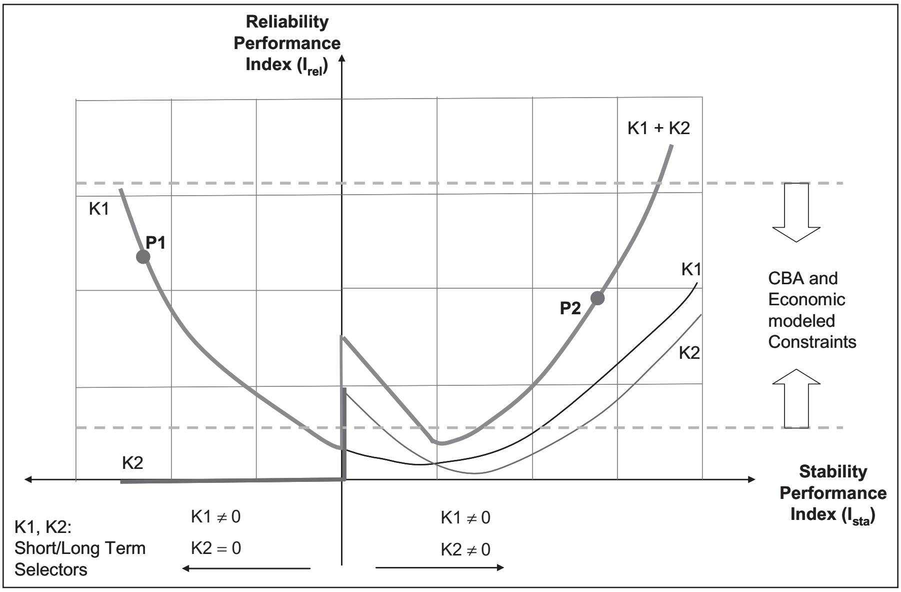


Figure 1.6. Sketch of the sustainability objective function.

*where:*

$I_{rel}$ : Reliability index vector of the network
$I_{sta}$ : Stability index vector of the network
`$\beta_{rel}$, $\beta_{sta}$ : Scaling multipliers for the index vectors
$CBA_{oper}$ : Functional of Cost-Benefit for the operation of the network
$h_{econ}(t)$ : Economic constraints (hard and soft)
$\mu_i^T$ : Penalty on the economic constraints
$k_1$, $k_2$ : Term selectors
$k \in \{0, 1\}$ : Long term, short term values of $k$
$i \in \{1, NS\}$ : Set of subsystems in the network
$t \in \{0, T\}$ : Time frame

Finally, in an attempt to evaluate the constrained multi-objective functions, analytical hierarchical process and Pareto-optimal analysis could be used to assign priority and ranking to control options used in the general formulation of the optimal power flow problem. The next section of the chapter highlights topical areas of research towards this goal.

## 1.5 TEST BEDS FOR EPNES

### 1.5.1 Power System Model for the Navy

To build a High Performance Electric Power System (HPEPS) model for the U.S. Navy ship system, a detailed physical model and mathematical model of each component of the ship system is needed. For an integrated power system, at minimum, the generator model, the AC/DC converter, DC/AC inverter and various ship service loads need to be modeled. Because the Navy ship power system is an Integrated Power System (IPS), an AC/DC power flow program needs to be specially designed for the performance evaluation and security assessment of the naval ship system. Accurate contingency evaluation of the Naval Integrated Power System should be based on a comprehensive system model of the naval ship system.

Figure 1.7 is the AC generation and propulsion test-bed. It comprises the following elements:

- The prime mover and governor is a 150 Hp four-quadrant dynamometer system
- The synchronous machine (SM) is a Leroy Somer two bearing Alternator part number LSA432L7. It is rated for 59 kW (continuous duty) with an output line-to-line voltage of 520–590 $V_{rms}$. The machine is equipped with a brushless excitation system and a voltage regulator.
- The propulsion load consists of the propulsion power converter, induction motor, and load emulator:
    - A rectified, DC-link, inverter propulsion power converter

- The propulsion motor is a 460 $V_{rms}$ L-L, 37 kW, 1800 rpm, Baldor model number ZDM4115T-AM1 Induction Machine (IM).
- The load emulator is a 37 kW four-quadrant dynamometer.

- The 15 KW ship service power supply (PS) consists of 480 V 3-phase AC diode rectifier bridge feeding a buck converter to produce 500 V DC. These converters provide the logical interconnection of the AC and the DC test-beds. In the future, an alternative, thyristor-based active rectifier converter may be available.
- A future pulsed load
- The harmonic filter (HF) is a wye-connected LC arrangement. The effective capacitance is 50 mF (which is implemented with two 660 $V_{rms}$ 25 mF capacitors in series) and the design value of inductance is 5.6 mH (rated for a 40 A peak, without saturating).

Figure 1.7 also shows the DC zonal ship service distribution test-bed. It is composed of the following elements:

- Each 15 kW ship service power supply consists of a 480 V 3-phase AC diode rectifier bridge feeding a buck converter to produce 500 V DC. These converters provide the logical interconnection of the AC and DC testbeds. In the future, an alternative, thyristor-based active rectifier converter may be available.
- The 5 kW ship service converter modules convert 500 Vdc distribution power to intra-zone distribution of approximately 400 Vdc.
- The 5 kW ship service inverter modules convert the intra-zone 400 V dc to three phase 230 V AC powers.
- The Motor controller (MC) is a three-phase inverter rated at 5 kW.
- The constant power load (CPL) is a buck converter rated at 5 kW.

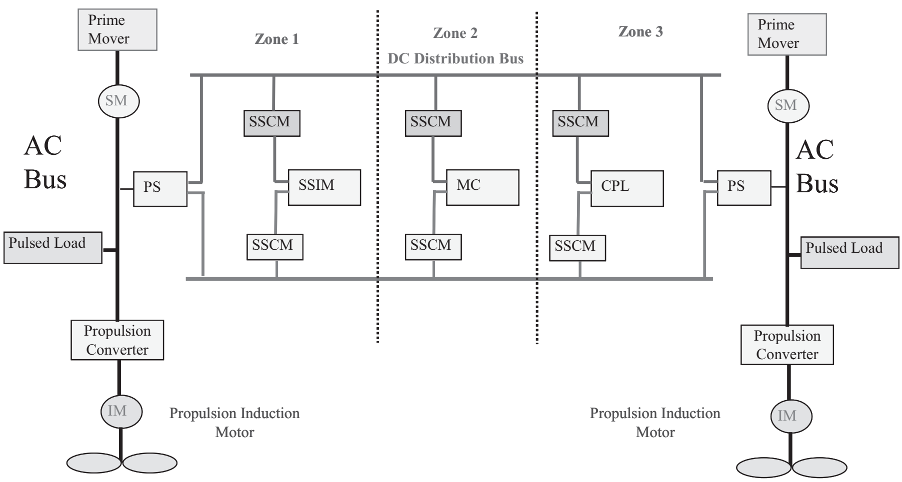


Figure 1.7. Navy Power System Topology.

## 1.5.2 Civil Testbed—179-Bus WSCC Benchmark Power System

The WSCC benchmark system contains 179 buses, 205 transmission lines, 58 generators, and 104 *equivalenced* loads on the high voltage transmission circuits. The system is operated at 230-, 345-, and 500-kV. Figure 1.8 shows a HV single line diagram of this system.

Also, embedded in this system are several control devices/options that include ULTC transformers, fixed series compensators, switchable series compensators, static tap changers/phase regulators, generation control, and 3-winding transformers. At 100 MVA System base, the total generation is 681.79 + j156.34 p.u. and the total load is 674.10 + j165.79 p.u.

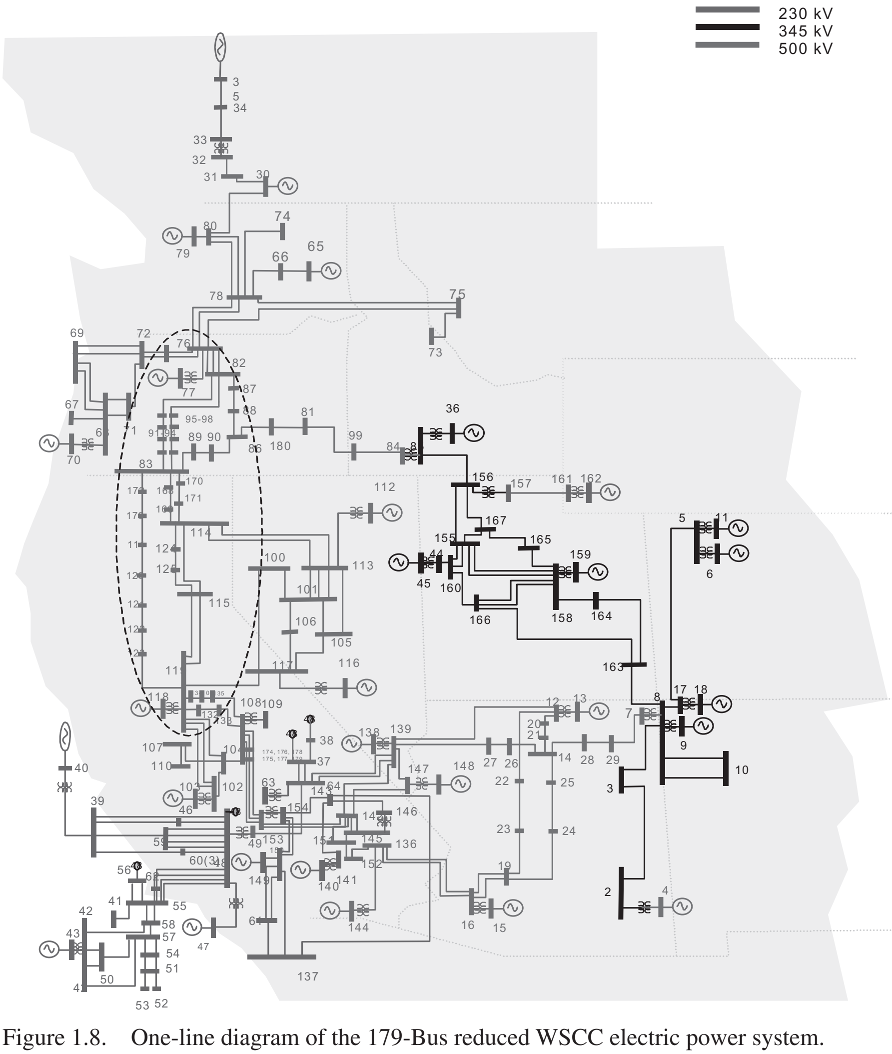


Figure 1.8. One-line diagram of the 179-Bus reduced WSCC electric power system.

## 1.6 EXAMPLES OF FUNDED RESEARCH WORK IN RESPONSE TO THE EPNES SOLICITATION

### 1.6.1 Funded Research by Topical Areas/Groups under the EPNES Award

The awarded research topical areas are grouped in four areas consisting of:

**(1)** Group A: system theory, security technology/communications, micro-electro-mechanical systems (MEMS);

**(2)** Group B: economic market efficiency;

**(3)** Group C: interdisciplinary research in systems, economics, and environment;

**(4)** Group D: interdisciplinary education. The titled of the awards for each of these groups are listed below. The four joint NSF/ONR awards are marked with an asterisk, *.

***Group A: Systems Theory, Security, Technology / Communications, Micro Electro Mechanical Systems (MEMS)***

- University integrated Micro-Electro-Mechanical Systems (MEMS) and advance technology for the next generation / power distribution;
- *Dynamic models in fault tolerant operation and control of energy processing systems;
- Unified power and communication infrastructure for high security electricity supply;
- Intelligent power router for distributed coordination in electric energy processing networks;
- *High confidence control of the power networks using dynamic incentive mechanism;
- Planning reconfigurable power systems control for transmission enhancement with cost recovery systems.

***Group B: Economic Market Efficiency***

- Forward contracts, multi-settlement equilibrium and risk management in competitive electricity markets;
- Dynamic game theoretic models of electric power markets and their vulnerability;
- Security of supply and strategic learning in restructured power markets;
- Robustness, efficiency and security of electric power grid in a market environment;
- *Dynamic transmission provision and pricing for electric power systems;
- Pricing transmission congestion to alleviate stability constraints in bulk power planning.

***Group C: Interdisciplinary Research in Systems, Economics, and Environment***

- Designing an efficient and secure power system using an interdisciplinary research and education approach;
- *Integrating electrical, economics, and environmental factors into flexible power system engineering;
- Modeling the interconnection between technical, social, economics, and environmental components of large scale electric power systems;
- A holistic approach to the design and management of a secure and efficient distributed generation power system;
- Power security enhancement via equilibrium modeling and environmental assessment (Collaborative effort among three universities);
- Decentralized resources and decision making.

***Group D: Interdisciplinary Education Component of EPNES Initiative***

- Development of an undergraduate engineering course in market engineering with application to electricity markets.
- Educational component: Modeling the interaction between the technical, social, economic and environmental components of large scale electric power systems.
- A technological tool and case studies for education in the design and management of a secure and efficient distributed generation power system.

## 1.6.2 EPNES Award Distribution

To date, a total of 17 awards, valuing more than U.S. 19 million, were granted to the winning proposals from 21 universities under the EPNES initiative, supporting the research activities of faculty and students. The topical areas and involved schools are listed in the previous section of this paper. Figure 1.9 shows the distribution

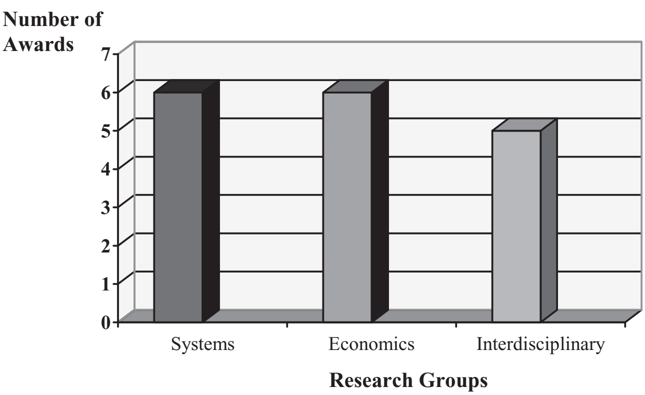


Figure 1.9. Distribution of EPNES awards among interdisciplinary research groups.

among the Systems, Economics, and Interdisciplinary groups. These three groups are spanned by the requirements of Education and Benchmark Systems.

## 1.7 FUTURE DIRECTIONS OF EPNES

1. Promote the implementation of the current EPNES goals by researchers for adoption in the private sector and the Navy. The underlying objective of EPNES is to unify cross-disciplinary research in systems theory, economics principles, and environmental science for the electric power system of the future.
2. Continue to involve industry and government agencies as partners. For example, utilize EPNES as a vehicle for collaboration with U.S. Department of Energy in addressing future needs of the industry such as blackouts, intelligent networks, and power network efficiency.
3. Include more mathematics and system engineering concepts in the scope of EPNES. This includes development of an initiative that is geared to include applied mathematics, systems theory, and security in addressing the needs of the power networks.
4. Extend the economic foundations from markets to cost-benefit analysis and pricing mechanisms for the new age high-performance power networks, both terrestrial and naval.
5. Continue to support reform in power systems with better education pedagogy and more adequate curricula in the colleges and universities. Enforce 'learning and research' via collaboration for increased activities that cut across engineering, science, mathematics, environmental, and social science disciplines. Promote and distribute the new education programs throughout the universities and colleges.
6. Use EPNES as a benchmark for proposal requirements of other NSF initiatives. Subsequent proposals submitted by Principal Investigators to an NSF multidisciplinary announcement should not be limited to the component level of problem-solving but should reflect a broader and more comprehensive interdisciplinary thinking, together with a plan for real-time implementation of the research by the private sector. Future initiatives will be structured toward the areas of Human Social Dynamics (HSD), Critical Cyber Infrastructure (CCI), and Information Technology Research (ITR).

## 1.8 CONCLUSIONS

In this vision of the Electric Power Networks Security and Efficiency (EPNES) initiative, we have described the framework of interdisciplinary research work and the underlying needs that drove the initiative. EPNES has many challenging research and education tasks to be finished, which will require state-of-the-art knowledge and technologies to solve. However, the research results of the EPNES project will be significant and useful for the improvement of both terrestrial and naval power system performance in terms of survivability, sustainability, efficiency and security as well as environment.

The funded research under the EPNES collaboration illustrates the breadth of the initiative and we believe that the research results will enhance power system security reliability, and affordability, help efforts for environment protection, and maintain high system sustainability. The results of EPNES will have significant impact to the education of students in multiple fields of engineering, science, and economics.

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