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 US Navy power system topologies, under varying disruptive or catastrophic events. Because the US Navy ship power system is an integrated power system (IPS) consisting of AC/DC components and several operational frequencies, they require different modeling and simulation tools than those being used in standard industrial or bulk AC power systems. Accurate contingency evaluation of the Naval Integrated Power System should be based on a comprehensive system model of the naval ship system. For both systems, robustness characteristics are 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, there must be appropriate educational resources 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, an interdisciplinary research-based curriculum that prepares engineers, economists, and scientists to plan and operate power networks is necessary. To accomplish this goal, it must be recognized that these networks are sociotechnical systems, meaning that successful functioning depends as much on social factors as technical characteristics. Robust power networks are a critical component of larger efforts to achieve sustainable economic growth on a global scale.

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 researchers from engineering, environmental, and social-economic sciences together. 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 socioeconomic 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 that incorporate advanced systems theory, economics, environmental science, policy and technical issues must be developed. 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-cutting courses are financial engineering, power market and cost-benefit analysis, and power environment, advanced 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 jointly 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 be posted on the host institution’s
website. Furthermore an assessment strategy should be applied on an ongoing basis to ensure sustainability of the program and its impact in attracting students and improving workforce competencies in developing efficient and reliable power systems.

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 [1,2]. 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 environments transitions and 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 to better prepare the workforce 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/ [3].

1.2.1 The Power System Modeling and Computational Challenge

Power system architectures today 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 to take 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 taking into consideration the peculiarities of both systems is desirable.

1.2.3 New Interdisciplinary Curriculum 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 educational material for undergraduate and graduate level students. The initiative supports outreach and curriculum improvements to most effectively educate the future workforce via an interdisciplinary research scope with 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 the 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 indexes 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.

**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 indexes 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 that can be a US utility system or the EPRI/WSCC 180-bus system [4]. Also the US Navy benchmark integrated power system (IPS) system designed by Professor Edwin Zivi of the US Navy Academy is a representative Navy test-bed example. Both systems consist of generator models, transmission networks and interties, various types of loads and controls, and new technology control devices such as FACTS, AC/DC transmission, and distributed generation. To ensure that all elements of EPNES are considered by the researchers, including the issues of environmental constraints (e.g., emission from generator plant devices), public perception, and pricing and cost parameters for economic and risk assessment.
Using 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 trade-off (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 done using the advanced optimization techniques. We 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 are capable of adapting to different situations, self-reconfiguring, and sustaining faults and yet prove to remain reliable and affordable.

1.4 TEST BEDS FOR EPNES

1.4.1 Power System Model for the Navy

To build a high-performance electric power system (HPEPS) model for the US 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 1.3 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 to 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:
  - The inverter propulsion power converter has a rectified, DC link.
  - 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.
Figure 1.3  Navy power system topology.
A pulsed load is a purely AC load connected close to the generator terminal for representation of the pulse weaponry. It operates on a base power of 1 kW and requires 100 kW, when fired, from the AC zone of the ship power system.

The harmonic filter (HF) is a wye-connected LC arrangement. The effective capacitance is 50 μF (which is implemented with two 660 Vrms 25 μF capacitors in series) and the design value of inductance is 5.6 mH (rated for a 40 A peak, without saturating).

Also in Figure 1.3, the DC zonal ship service distribution test bed is shown. 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 test beds. In the future an alternative, thyristor-based active rectifier converter may be available.
- The 5 kW ship service converter modules convert 500 V DC distribution power to intrazone distribution of approximately 400 VDC
- The 5 kW ship service inverter modules convert the intrazone 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.

1.4.2 Civil Test Bed—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 [4]. Figure 1.4 shows a HV single line diagram of this system. Also embedded in this system are several control devices/options, including ULTC transformers, fixed series compensators, switchable series compensators, static tap changers/phase regulators, generation control, and 3-winding transformers.

At the 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.

1.5 EXAMPLES OF FUNDED RESEARCH WORK IN RESPONSE TO THE EPNES SOLICITATION

1.5.1 Funded Research by Topical Areas/Groups under the EPNES Award

The awarded research topical areas are grouped in four areas: (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 a star (*).
Figure 1.4 One-line diagram of the 179-bus reduced WSCC electric power system.


- 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.

**1.5.2 EPNES Award Distribution**
To date, a total of 17 awards, valuing over 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 1.5 shows the distribution among the systems, economics, and interdisciplinary groups. These three groups are spanned by the requirements of education and benchmark systems.

### 1.6 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 US 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 would be structured toward the areas of human social dynamics (HSD), critical cyber infrastructure (CCI), and information technology research (ITR).

1.7 CONCLUSIONS

In the electric power networks security and efficiency (EPNES) initiative we have described, we envision a framework of interdisciplinary research work. EPNES has many challenging research and education tasks that will require state-of-the-art knowledge and technologies to complete. Already the research results of the EPNES project hold promise for the improvement of both terrestrial and naval power system performance in terms of survivability, sustainability, efficiency, and security as well as for protection of the environment.

The funded research under the EPNES collaboration demonstrates much breadth of initiative. We believe that these research results will significantly contribute to the education of future engineers, scientists, and economists.

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