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Interdisciplinary Education through "Edu-tainment": Electric Grid Resilient Control Systems Course

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Interdisciplinary Education through "Edu-tainment": Electric Grid Resilient Control Systems Course

Introduction

As energy companies and governments attempt to get more from the existing power grid and other critical infrastructures, more automatic control systems are being applied [1-2]. With this greater reliance on network-based, digital automation and the stresses of pressing existing infrastructure for greater performance, the power grid and underlying systems have become more susceptible to both malicious attacks and unexpected, natural threats. Governments and other stakeholders have chosen to address infrastructure issues by the implementation of a smarter grid. In the smart grid, operators and control systems supervise power generation, distribution, transmission, and loads to utilize these assets most efficiently[3]. Such extensive monitoring and control over a distributed system cause complexity that challenge systems designers and human operators in new ways. In addition, cyber vulnerability of these systems has been illustrated in many recent articles on state-sponsored attacks to electric power systems and other similar infrastructure for natural gas, water and communications[4]. It is therefore critical in the next generation of control systems that resilience plays a large and critical role in the grid design and development. Resilient control systems is a field of research that seeks solutions to the complexity through a holistic approach that combines cognitive science, computer security, communications, and control systems. To enable future researchers and practitioners to assist with designing more resilient systems, science, technology, engineering and mathematics education needs to incorporate interdisciplinary topics. While electrical engineering and computer science programs in the nation include a cyber security perspective, few if any have focused on the unique control system aspects. Human cognitive aspects are most definitely not addressed in technology education discourse. To this end, a class and education tools in resilient controls systems have been created.

This paper describes a class and educational entertainment, "edu-tainment," tool developed over the past two years to give students a broader perspective and appreciation of the "big picture" of complex systems such as critical infrastructure. Understanding of the interdisciplinary nexus of control systems, human systems, economics and cyber security is provided through the study of resilient control systems as applied to the electric power grid. The course was developed in collaboration of the University of Idaho, Boise State University, Idaho State University, Colorado State University, the University of Minnesota, Idaho National Laboratory, and Idaho Regional Optical Network. The edu-tainment tool is an expansion of a basic grid simulator into a gaming environment, where students play and learn. Additionally, students were challenged with conceiving and developing concepts to add realism and complexity to the game platform.

This paper is organized in sections beginning with a section describing the structure and goals of the class. The next section gives an overview of the game. The results section describes outcomes in the level of engagement achieved by the students at the events and the activities, culminating with the resilient control systems class, where mentors guided students, using the Grid Game as a vehicle to learning about the electric grid and resilient controls. Finally, a conclusions and possible paths forward are given.

Topics in Resilient Controls

Benefiting from an already ongoing interdisciplinary field of study[5], a course was created to establish a perspective for college students on the unique challenges of automation in our society. The course was broadcast to the participating universities through interactive web based lectures. The course was first organized in the Fall 2013 as a series of lectures in resilient controls, without a central application theme. The course was refined for Fall 2014 to include institutions outside of Idaho and incorporate a focus on the application of electric power micro-grids. Resilient control systems architecture, as shown in , offers additional perspective on topics of a subset of interdisciplinary topics that impact real world critical infrastructure. The course addressed how systems fail due to threats from cyber security, human error and complex interdependencies, and how the application of resilient control system technologies addresses these challenges. The broad range of topics in resilient control systems would typically be addressed in different course, in different departments or colleges. When taught together, a course becomes relevant to multiple engineering and science disciplines, drawing students into the sometimes challenging but equally rewarding multidisciplinary conversation. The course has the potential to lead to the desired academic and social outcome of more broadly developed engineers and scientists with ability to connect the "languages" of the distinct disciplines to tackle increasingly coupled problems in complex systems.

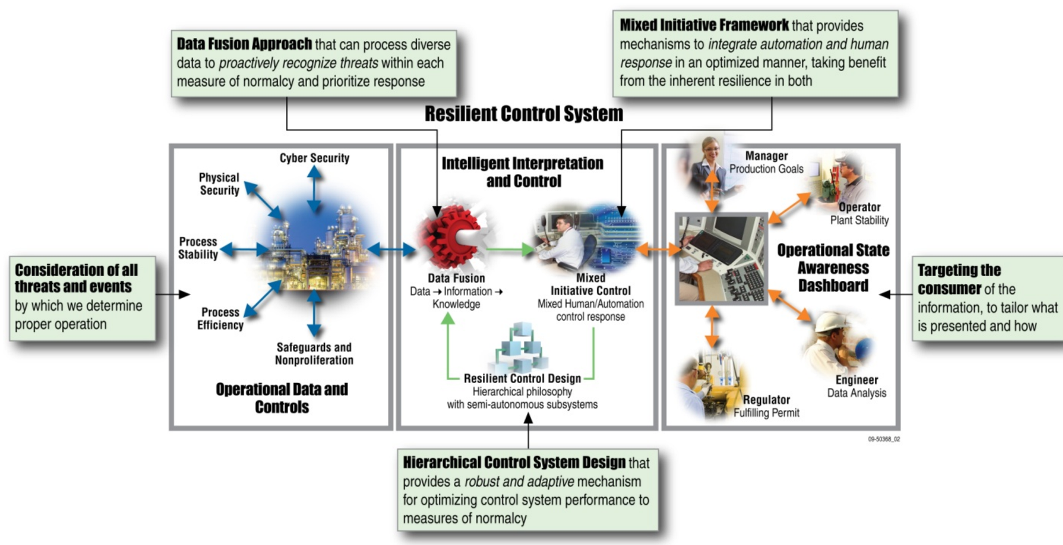

Figure 1. Resilient Control System Framework

The power grid was chosen due to its importance to support of modern society, the distributed and complex nature of the control systems, and the current and planned efforts to modernize through smart grid initiatives. The goal of the course is for students from multiple disciplines, ranging from college juniors to graduate students, to arrive at an intuitive perspective on the control, human, and cyber security aspects of the electric grid through a game-ified grid simulation. Understanding of the multiple challenges and failure modes in critical infrastructure (e.g. growth without investment, arbitrage, and malicious actors), is achieved intuitively through the "Grid Game," shown in Figure 2. That intuitive study, though important in its own right, is aimed at developing curiosity to engage students in attacking the underlying details of the various aspects affecting the technology outcomes.

The course was divided into a series of weekly sessions covering a survey of resilient control topics as well as sufficient background discussion on the electric power grid to prime students from a variety of levels in engineering studies for the discussions. The series of lectures began with the following weekly topics with lectures by both academics and professionals:

1. Overview of the course, the grid game competitions, and the relationship to resilient control topics
2. “Hands on” demonstration with a scale model micro-grid on a wall
3. Power grid architecture, modeling, and microgrids
4. Power grid controls
5. Power grid architecture and cyber security
6. Human-grid interaction[6]
7. Multi-level agent based controls[7-8]
8. Demand response and building automation.[9]

The weekly sessions provided students with background on a subset of the key topics required to obtain a basic understanding of power control systems and key elements of resilient controls, such that the students could apply the concepts in a final project.

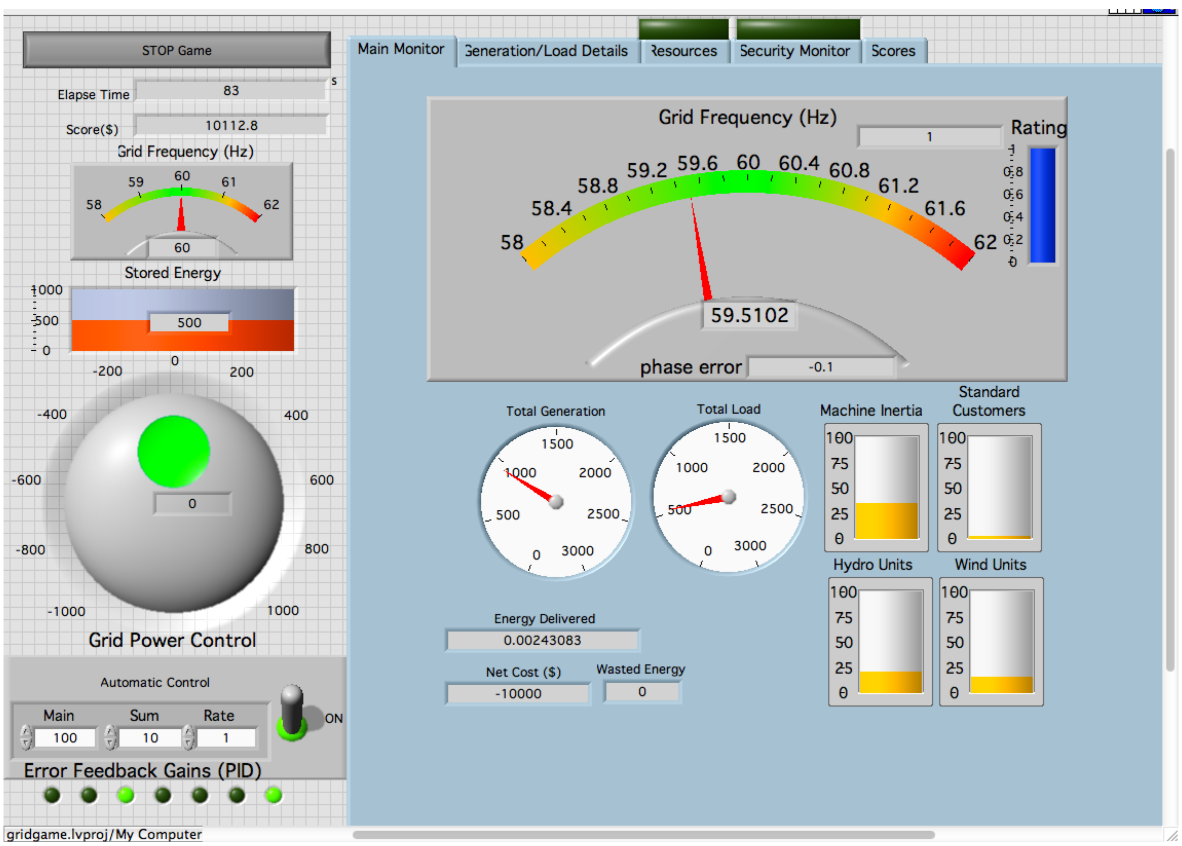

Figure 2. Grid Game Screen Capture: Main Screen

Formal or informal assignments to consider the aspect of resilient control systems covered in a given session, where given by each instructor. For example, the Human-grid interaction session asked the students to review the Grid Game from a human factors perspective in a heuristic evaluation of the game user interface.

The course continued with a series of “challenge” presentations devised to provoke thought and investigation. The students where challenged to chose a final project that incorporated resilient control improvements to the Grid Game that included but not limited to:

- Enhancing the control system
- Representing cyber and physical threats more realistically
- Applying demand response approaches.

The students participated in Grid Game play as a group, such that, they could buy and sell power to each other and also experience virtual cyber security attacks on their microgrid. Implicit lessons in the game include the need for preparation for potential threats and possible dramatic changes in the generation and load profile. The objective of the game to score more points than your competing microgrids provides an economic driver that encourages players to grow their customer and generation base in a balanced manner to avoid potential pitfalls of rapid growth. Even in a friendly competition, students expressed that they experienced a visceral response to hearing the computer mouse clicks of the Red Team preparing a cyber attack. This anecdotal note shows the importance of cognitive aspects of the human in the loop experiencing pressures that an automatic control system does not experience.

Students were finally directed to use the background provided by the class material and their own experience to produce projects that developed concepts for improving the realism, entertainment and education value of the Grid Game for future improvement of the resource. The outcomes are discussed in the results section.

The Grid Game Edu-tainment Platform

Power Infrastructure System

The Grid Game grew out of a desire to provide students with a simple simulation environment of a microgrid during the first year the resilient control systems class was taught. The simulator was turned into a multi-level single player game to provide additional entertainment while players achieved an intuitive feel for running a simulator with both open loop and closed loop feedback control. Demand response and the ability to curtail industrial loads were also included. The goal was to create a simulator that has realistic feel and that is implementable on a standard personal computer or even a portable device. Noting that there are arguments over the accuracy of the physics of purely entertainment games[10], the Grid Game seeks reasonable fidelity but will readily admit to making simplifications that may not be entirely realistic for the sake of playability or due to limited resources. This version may be downloaded at http://gridgame.inl.gov/. Part of the challenge to the class was to interrogate the realism of the game and suggest improvements where possible.

At the core of the game is a simple simulator that emulates the frequency variations of the electric grid as driven by the spinning machines that help maintain frequency stability through the kinetic energy stored in the flywheel effects of the rotors of the generators and the synchronous machines attached to the electric grid. An important concept of spinning inertia's role in maintaining stability of the grid can be explained in a simple manner. The physics described through the governing differential equation can be explained simply as: "If generation is greater than load consumption: the frequency goes up and energy is added to the spinning machines. If the load becomes bigger (e.g. more lights or heaters are turned on) or a generator goes off line, the frequency goes down, because some of the kinetic energy is removed from the spinning machines to supply the deficit." The concept is simple enough to explain to elementary and secondary students and others without the mathematics background, however, is complex enough to explore control systems deeply, since the differential equation is non-linear and possibly time-variant with the moment of inertia changes when generation or synchronous machine based loads are added or removed from the grid. The differential equation of calculating the frequency of the microgrids, known as the swing equation,[11] is give as:

$$P_g - P_e = J\omega_m \frac{d^2\delta}{dt^2}$$

where P_g is the power generated by the heat source or mechanical forces connected to the turbine and generator, $P_e$is the electric load or power being consumed, J is the moment of inertia of the spinning machine, ω_m is the angular velocity of the reference spinning machine which is proportional to the grid frequency and δ is the angular position of the generators rotor relative to the reference frequency (i.e. the rate machines angular velocity is changing due to the imbalance). The microgrid is considered as one bulk node; so, the reference frequency will increase or decrease based on the power generation and load imbalances of the local grid. To arrive at sufficient fidelity to make the game have physical realism, yet allow real time computation the equation is implemented as the simplified difference equation:

$$\Delta\omega_m = \frac{(P_g - P_e)\Delta \mathrm{t}}{J\omega_m}$$

with $\Delta \mathrm{t} = 0.0167\mathrm{s}$, chosen to be small enough to provide a reasonable degree of accuracy in the calculation of the change in frequency at each game step. The load and generation are driven by recorded system data, which has been made available through a previous education outreach effort by Idaho Falls Power municipal electrical utility and the Wind for Schools program (http://wind-for-schools.caesenergy.org/). The data set contains hydro-electric generation, wind generation, load and meteorological data. To make the game more dynamic, the data is played back more rapidly than real-time as one ten-minute sample of data to one second of game play, or 600 times faster than real-time. One year of historical data has been collected and repeats as necessary for the game to continue. The data set contains periods of power outages as well as seasonal and diurnal cycles. The net power imbalance is calculated as:

$$P_a(t) = P_g - P_e = U_h G_h(t) + U_w W(t) + S(t) + C(t) - U_c L_r(t) - \sum_i L_i D_r(t)$$

where U_h, U_w, and U_c are the number of hydro generation units, wind generation units, and residential customer units that are multiplied by the hydro generation, $G_h(t)$, wind speed, $W(t)$, and residential load, $L_r(t)$, from the municipal utility data. The net power added from the controllable storage source, $S(t)$, adds to the generation or absorbs power from grid to enable the player to have a control input to regulate the frequency. Additionally, C is the net power into the microgrid of contracts bought and sold between microgrids. The industrial loads, L_i, are summed to find the total amount of power being consumed by constant loads, when not curtailed through a demand response action by the microgrid manager (each player manages their own microgrid). The state of demand response is given as $D_r = 0$ for curtailed load and 1 otherwise.

Scoring and Challenges

Players build up their electric grid, as they accumulate points, by purchasing more generation units, energy storage capacity, and acquiring more residential and industrial customers. The moment of inertia of the microgrid is increased with addition of hydro-generation or industrial loads, on the expectation that they would contain synchronous machines. Inertia is not increased with addition of residential load or wind turbines, which have a spinning mass, but are not generally utilized to add to the moment of inertia to the grid. The game score is tied to the economics of the grid operations. The score is determined, primarily, by the amount of energy provided to customers multiplied by a cost per energy unit. Additionally a scoring metric is calculated between 0 and 1 as a multiplier to the energy cost based on how well the player regulates frequency, overall phase angle relative to a reference, as well as some tertiary factors based on avoiding rapid changes to the use of the storage source. Players may also use points to protect their grid by purchasing cyber security tools such as firewalls and virus scanning tools. The costs have been assigned in a way to allow player to accumulate assets in a reasonable amount of playtime. Realism in portraying costs and credit markets are potential locations for game improvement through student projects.

The microgrid operator is challenged through the numerous human interaction opportunities that exist in the game, which are reflected in the score. The players must regulate frequency to avoid having the machines on the grid from "tripping" to protect themselves from over or under frequency conditions. In the game, grid operation is stopped and restarted if the grid frequency strays outside a two-Hertz tolerance. The player is penalized by losing a portion of their residential customers and the last industrial load customer that was recruited. The storage source that represents a simplified view of a battery or other mechanical storage mechanism (e.g. pumped storage) is the low level control provide to the player for regulating frequency. The energy limited storage source is used to absorb power when excess is being generated and supply power when loads are high.

A control knob is provided on the user interface (on the left in Figure 2) for manual control of the use of the storage source. The storage acts as a fast responding source, as would be the case with a power converter interface to transfer real power to and from the grid. For initial simplicity, the Grid Game neglects voltage regulation that could also be realized through the use of the STATCOM for reactive power compensation. Players are encouraged to practice manual control the microgrids in this manner for two reasons: one to gain an appreciation for automatic control by recognizing the mundane task of manual control is monotonous and prone to human errors; and, two, a cyber-physical attack or other failure on the control system may make it necessary to take over manual control.

The automatic control system consists of a frequency sensor that feeds back through a proportional, integral, differential (PID) set of gains. Students can experiment with how different gain values change the response of the grid to changes in load and generation. An objective is to optimize the scoring metric by changes to the PID gains. The system of generation, loads, battery system and closed loop control is summarized in .

With the automatic control engaged, the player takes on the strategic role, while maintaining a supervision of the operations of the microgrid, of deciding how to grow their operations by investing their points. Decisions include how much storage to buy and the balance between purchasing contracts with renewable generation versus more traditional generation. Players decide when to apply demand response to industrial customers. Of course the microgrid must compensate the customer for the disruption. In multiplayer mode, a market to buy and sell energy contracts is available to allow excess power to be sold to other players' microgrids that need power. Finally players must decide what defenses to put in place to protect the cyber-physical interface against attacks on their system. In competition mode, a "Red Team" interface is available to the game coordinators to cause malware infections that may be a small financial

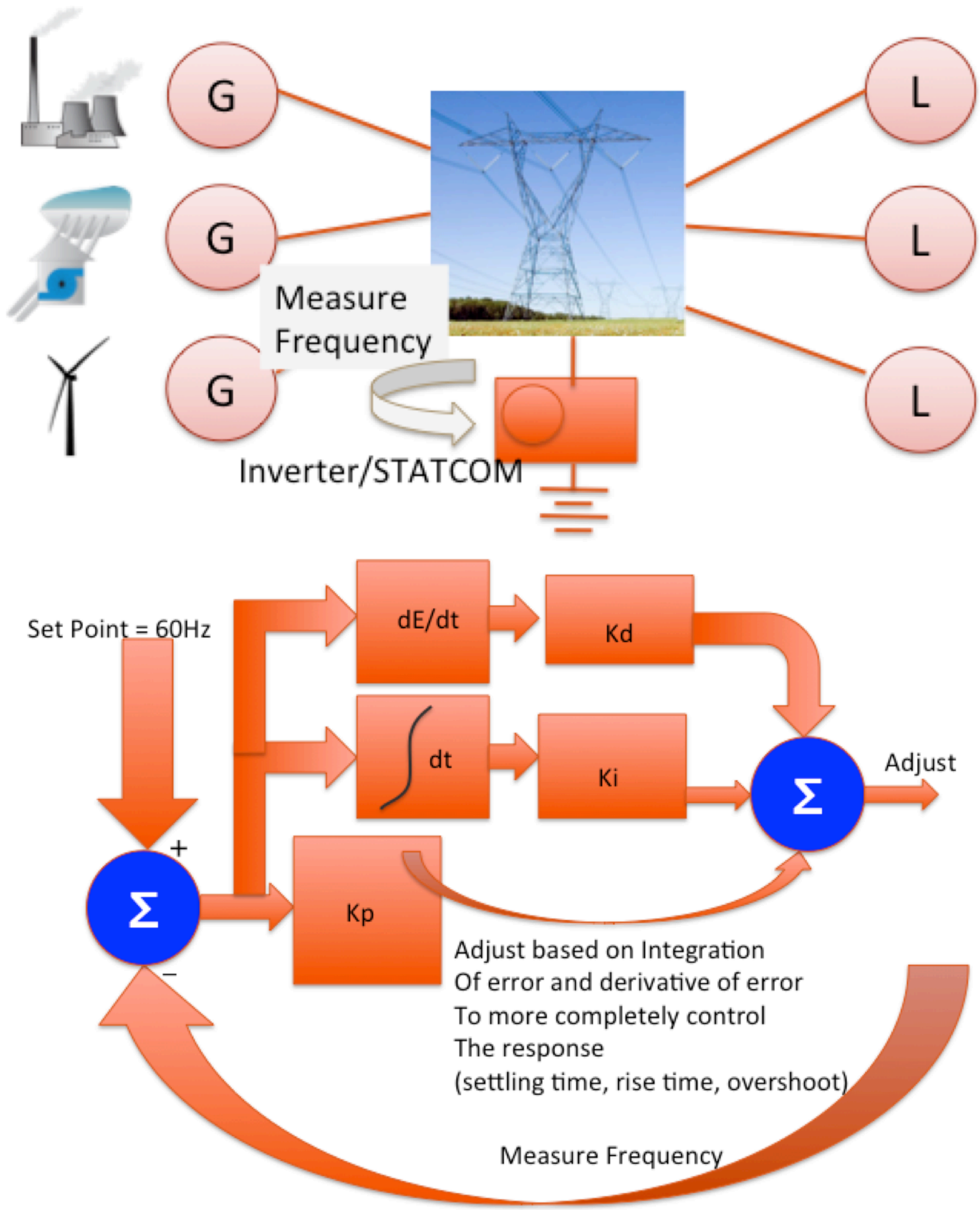

Figure 3. GridGame Control System Illustration

nuisance up to cyber-physical attack that can change the operation of the control system. The multiplayer architecture is shown in Figure 4. This version can be downloaded freely at http://gridgame.ironforidaho.net/download.html. Game features are accessed through the tabs on the user interface. Some of the features are shown in Figure 5.

Results

The results of introducing the game to students at various levels of education that are presently available are mostly anecdotal observations. Students have been challenged by the game in the activities in 2014 culminating in the resilient controls class. The game successfully engaged a

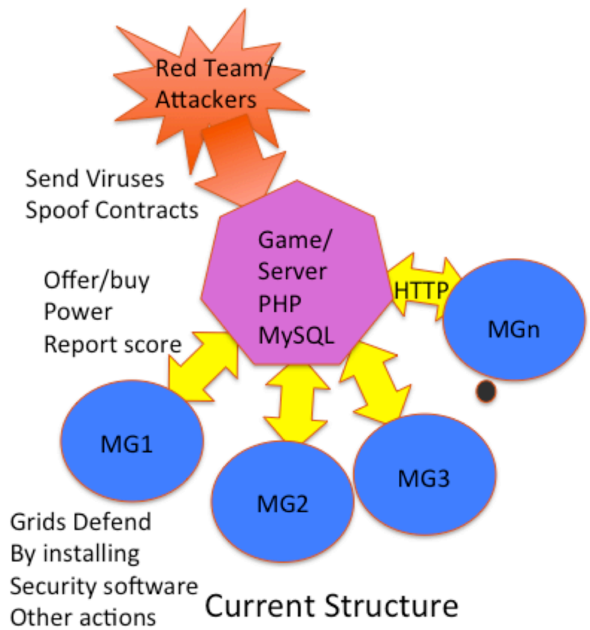

Figure 4. Grid Game Multiplayer Architecture

wide range of educational level by providing simple guided exploration of electric grid, for younger students and the general public, and more advanced control system features, with more mathematical aspects included for more advanced students and professionals. For example, turning a control nob to maintain the frequency of the grid provides an intuitive sense of a feedback control system. When followed with a discussion of the mechanisms of a feedback control system, high school or early college student were able to experiment with control gains on an intuitive basis; whereas, a senior or graduate student may apply control theory to optimize the tuning of a control system. Finally students with a deeper interest have the opportunity to develop ideas to improve the Grid Game platform by researching smart grids from a number of possible perspectives (e.g. control, human machine interface, economics, etc.). The following is a summary of the activities where the game has been employed.

Prior to the resilient controls class, the Grid Game has been utilized in several events to expose students at levels ranging from high school students up to graduate students as well as to engage the controls community and the public at large to grid technology. A stand-alone version was used at the vocational education exposition, Idaho State University Tech Expo (http://www.isu.edu/apptech/techexpo/index.shtml), for junior high and high school students in March of 2014. More than twenty students played the game and were given an education level appropriate introduction to power systems. Five of the students persisted to complete all of the levels of play. Game levels progressed from manual control to setting the control gains and finally making decisions about demand response as the amount of inertia and load variation were changed from round to round to increase the difficulty of the game.

In the spring of 2014, a group of undergraduate computer science students was recruited from Hashdump, Colorado State University's computer security club (http://hashdump.org/). The students coordinated with the game client developer to add the cyber security and market elements. The game server communicated to the game clients through a Hypertext Preprocessor (PHP) programming accessed through Hypertext Transfer Protocol (HTTP) to a MySQL database. The database tracks scores and status of the players with respect to cyber-attacks and the offered contracts on a virtual energy market. The microgrid client software polls the server periodically to maintain consistent state between the clients and update the scoreboard. An event was organized for Resilience Week 2014, Figure 6, where students from universities in the Denver, Colorado area competed with symposium attendees. The competitors had various degrees of success with some becoming flustered by the cyber security attacks while others managed rather well even against cyber-physical attacks that disabled the automatic control system for an extended duration. The event was covered in the local press.[12]

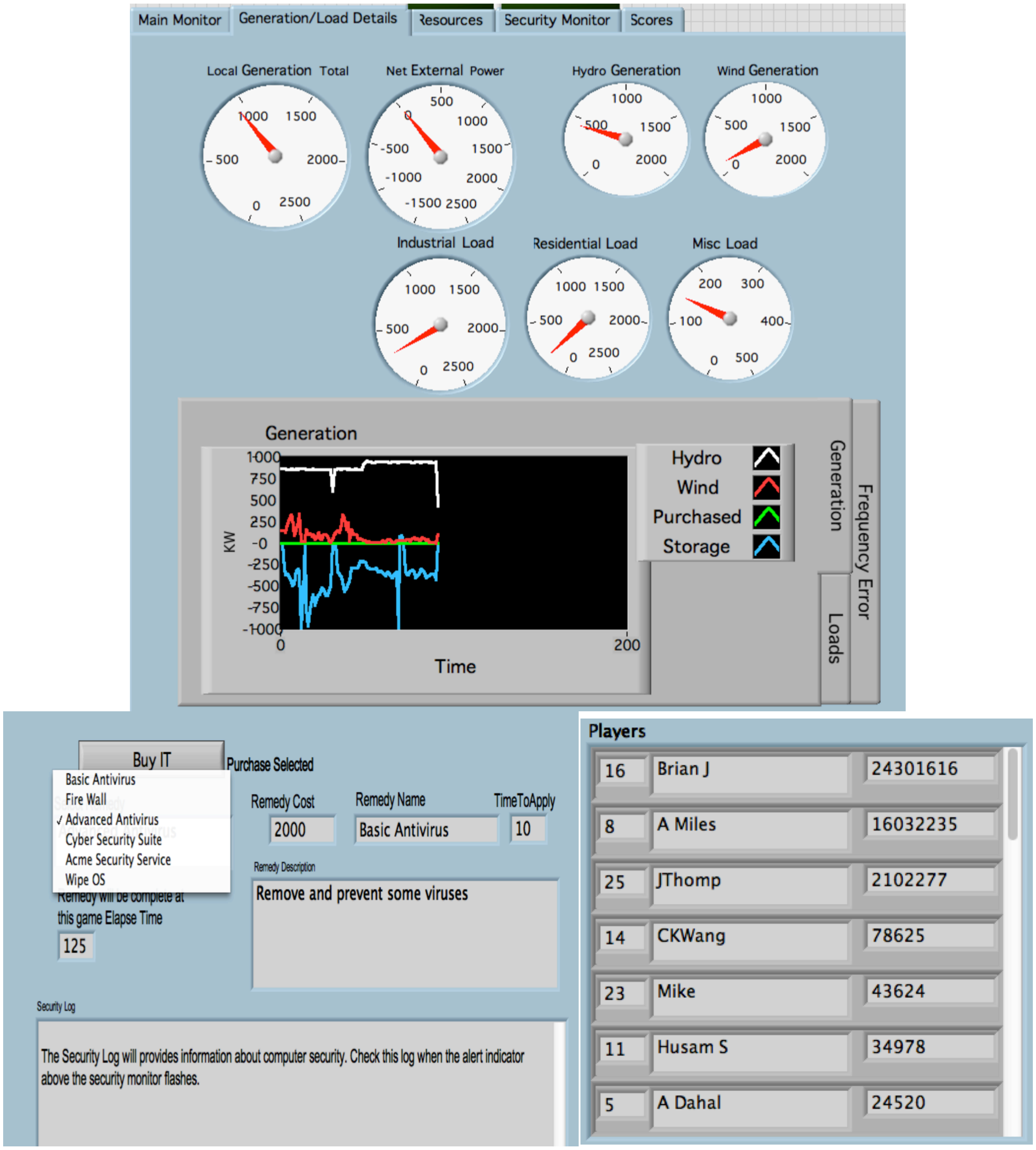

Figure 5. Grid Game screen captures showing trend data, cyber security interface and scoreboard.

The 2014 resilient control system class consisted of eleven students from two institutions, six university professors from five universities in three states, three research professionals from Idaho National Laboratory, and one student guest lecturer from the cyber security/server development team. Looking to a future grid with more renewable energy sources, students considered varyious methods to effectively stabilize their grid using advanced control strategies. They discovered that careful consideration is necessary to mitigate cyber attacks, and plan for energy needs. Students had the opportunity to compete with their peers, and learn through Grid Game competitions to consider enhancements that would make their power grid more efficient and resilient.

Figure 6. Competitors concentrate on building and managing their microgrid as the Red Team plans some unwelcome surprises.

The students were evaluated by the class instructors based on project presentations and reports based on quality, completeness, and demonstration of understanding of the concepts of resilient controls. Projects allowed students to creatively enhance resilience to a power grid by designing their own contribution to the game and resilient control systems. Students worked on individual projects or in teams of two.

Titles of student projects were:

- System Response to Supply and Load Constraints
- Expanding Hydro Unit Control to the Grid Game
- Adding Photovoltaic Generation to the Grid Game
- Adding Realism to the Infrastructure Components of the Microgrid
- Natural Gas Power Generation: A Grid Game Model
- Addition of Effects of Nature to the Grid Game

All projects showed students beginning to grasp the larger concepts of resilience controls in considering the complexity that arises from the interconnection of systems that must be considered in the operation of critical infrastructure: insights into the overlap of disciplines as seemingly diverse as power systems technology, computer science, human cognitive response, economics, meteorology, communications and the environment were captured in the reports and presentations. All of the projects produced viable ideas for additional features or resilient control components to the richness and realism of the educational tool. Thus, their engagement will augment the experience of future students that utilize the Grid Game. Several of the projects developed pseudo code or models to the level that developers can directly implement into future versions of the Grid Game.

Conclusion and Path Forward

Through the Grid Game events and the resilient controls class, outcomes have been anecdotally positive as shown in the engagement of the class, participants in the Grid Game competitions, and enthusiastic engagement of student developers to enhance the game. In one student's words, "This class provided a big picture of the grid that other classes in the engineering curriculum do not." Developments to the Grid Game and the resilient controls curriculum will continue through implementation of concepts developed by students in the class and the coordination of additional events. Engaging more student and instructor talent at the secondary, undergraduate and graduate level is enabling the edu-tainment platform to give an intuitive understanding to young students and the public in general. A public knowledgeable in the mechanism of critical infrastructure can make enhancements that require consumer cooperation possible. An enjoyable and challenging game that teaches realistic aspects could further this goal.

Acknowledgements

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