Improving Power Transmission Efficiency and Reliability through Hardware/Software Co-Design

B. McMillin, M. L. Crow, D. Tauritz, F. Liu, B. Chowdhury, and J. Sarangapani

Abstract — The transmission systems of tomorrow must incorporate advanced hardware and software technologies to increase safe utilization of existing facilities to increase reliable long-distance power transfer. However, while hardware technologies can provide the muscle for improved transmission system capabilities, software technologies are also needed to provide the intelligence to use these hardware technologies safely, securely, and effectively. To prevent system failures, future transmission systems must incorporate a combination of advanced hardware and software technologies to increase the safe utilization of existing facilities to increase reliable long-distance power transfer. Improvements are also needed in system-wide monitoring and distributed computer-based control to determine and react to system conditions quickly. Technologies such as these can protect the grid not only against traditional threats to reliability (such as storms and other natural events), but also against deliberate disruptions. Employing robust transmission controllers effectively requires a close development relationship between power electronics engineers and computer scientists such that the hardware development, algorithm development, system assessment, and software development are coordinated to ensure optimal performance. This paper describes these activities at the University of Missouri-Rolla's FACTS Interaction Laboratory.

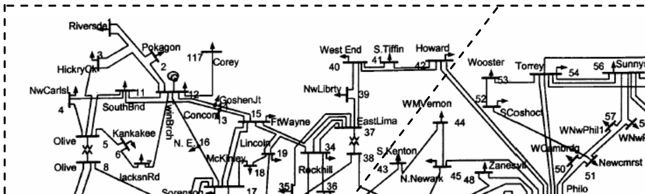
Index Terms—Power transmission control, Power transmission faults, Distributed Computing, FACTS, Computer Fault Tolerance

I. INTRODUCTION

Bulk power transmission systems form one of the largest complex inter-connected networks ever built and their sheer size makes control and operation of the grid an extremely difficult task. Grid control has historically been accomplished as a joint effort between generation and transmission entities under the auspices of the North American Electric Reliability Council (NERC) to maintain strict outage limits, frequency regulation, and resource planning [1]. Under recent federal deregulation mandates [2], however, generation and transmission of electric power must be owned and operated independently. Thus, transmission providers are often left having to coordinate large power transfers over numerous possible pathways with little or no means of coordinated control. This situation frequently leads to considerable congestion over major transmission corridors, resulting in transmission line overloads. With heavier power transfers, power systems are increasingly vulnerable to cascading failure in which a small series of events leads to a major blackout. Increased amount of transmission capacity can reduce these vulnerabilities, but at a significant cost in terms of economic and environmental impact.

An alternative to increasing transmission capacity is to make more efficient use of the existing power grid. This can be accomplished through increased control. One of the most promising new decentralized network controllers is the family of power electronics-based controllers, known as "Flexible AC Transmission System" (FACTS) devices [3]. FACTS devices have been shown to be effective in controlling power flow and damping power system oscillations. By controlling power flow on an individual line, power can be redirected to/from various parts of the power grid. Redirecting power flow allows for utilization of power lines that physics of power flow alone would not allow.

To manage the transmission system effectively using FACTS requires real-time coordination of the controllers to achieve a common goal. The distributed control of FACTS devices is not well understood due to the current lack of time-scale-based controls and decentralized operating paradigms for interacting FACTS devices. Power system operating paradigms are typically defined by time-scale: operating (long-term) control (minutes), dynamic control (seconds), and local control (fractions of seconds). Distributed algorithms in embedded computers in each FACTS device can coordinate actions by using a combination of local sensing, transmission system status, local code execution, and coordination with other embedded computers. Cooperative code execution and message passing over a communications network offer a high level of coordination. The combined FACTS devices, embedded computers, network, and distributed control algorithms form a distributed system called a FACTS Power System.



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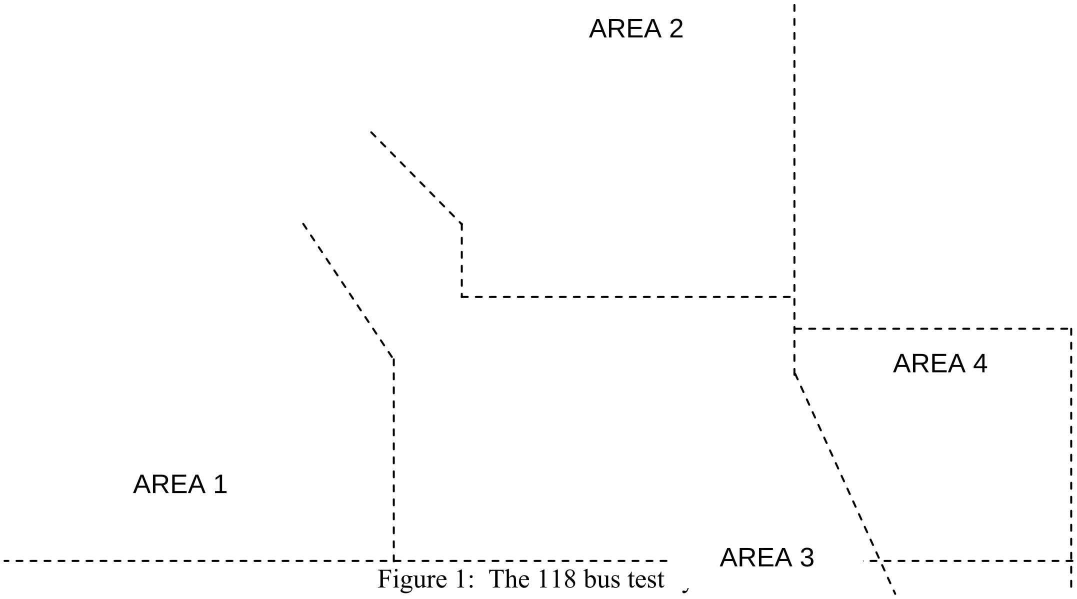

Figure 1: The 118 bus test

Significant concerns in deploying computer-coordinated power flow controllers are the fault tolerance and reliability and information security of the distributed system.

The remainder of this paper is organized as follows. Section II discusses power system vulnerabilities in terms of cascading failures and cyber computer system failures. Section III gives a background on FACTS devices. Section IV describes the related problems of developing placement and distributed control algorithms. Section V discusses fault tolerance and security considerations. Section VI discusses the hardware/software co-design process necessary for such a project and presents the resulting FACTS Interaction Laboratory (filpower.umr.edu) simulation testbed.

II. POWER SYSTEM VULNERABILITIES

Power systems are vulnerable in two main categories: physical failures of the electric power system components, and cyber failures of the associated control systems. In the FACTS power system, these failures can occur in combination. Cyber failures can cause the FACTS device to improperly control the power flow and physical line failures can overwhelm the hardware. To protect the system from a blackout resulting from a cascading failure, precursors for cascading failures need to be characterized such that the system can detect any vulnerable states it may be in to take corrective action. The most basic type of cascading failure precursor is a line overload.

The IEEE 118 bus power system was used as a model test system. The 118 bus power system was divided into four distinct regional areas (Areas 1 through 4) and system conditions that creates stress on these tie lines was identified as good candidates for causing a cascading failure scenario either through successive line overloading or through area isolation and islanding. The four principal areas are indicated in Figure 1.

The system was tested for cascading failure leading to a blackout. Only line outages were considered as contingencies. Generator outages or other dynamic problems were not considered. Since lines have limited capacity to carry power, they can become overloaded if the power flows on adjacent tripped lines are redistributed through them. As a first step, the effect of all single line contingencies on the system was exhaustively studied. Less than a quarter of the tested contingencies caused a serious overloading problem. The extent of overloading was used as a criterion for identifying further outages in the system. This process highlighted the specific path followed by a failure. In most of the cases, there were a finite number of lines that became overloaded. It is possible in the real system, that the highest loaded line may survive and some other line may trip. This possibility was considered in cases whenever there were a large number of overloads. The selection of the line to be outaged effects the number of events leading the system to blackout.

Out of all the possible single line contingencies, 37 outages were identified as potentially problematic. However, many of these result in a failure because they cause islanding of certain buses. Therefore out of the initial pool of 37 contingencies, only 15 contingencies were identified for further study. For example, the loss of line 4-5 causes overloading and leads to the subsequent loss of lines 5-11, 7-12, 3-5, 16-17, and finally 14-15. This scenario essentially limits the power delivered by transformer 5-8 to the north-western part of Area-1. The complete results of this analysis are presented in [4]. It can be observed that some of these contingencies cause wide-spread overloads, whereas other scenarios create overloads that are limited to just one particular area in the system. Therefore cascading failures can be prevents by mitigating the sequence of line overloads. FACTS devices, if placed on the proper lines and given proper control settings, can redirect power away from overloaded lines and/or areas. The next two sections give a short background on FACTS devices and describe algorithms for placement and control.

III. BACKGROUND ON FACTS DEVICES

The FACTS device under consideration is the UPFC (Unified Power Flow Controller) depicted in Figure 2 which has the functionality of both an SSSC and a STATCOM. The UPFC can control voltage, impedance, and phase angle based on control settings. This rapid control has been shown to be effective in achieving voltage support and stability improvement, thus allowing the transmission system to be operated more efficiently. The DOE National Transmission Grid Study released in May 2002 identified FACTS devices as playing a significant role in the "Intelligent Energy System" of the future. While FACTS devices offer increased network power flow controllability, the decentralized nature of their actions may cause deleterious interactions between them. Currently there is a general lack of understanding as to how to systematically stabilize system-wide dynamics via fast local modulation of FACTS devices.

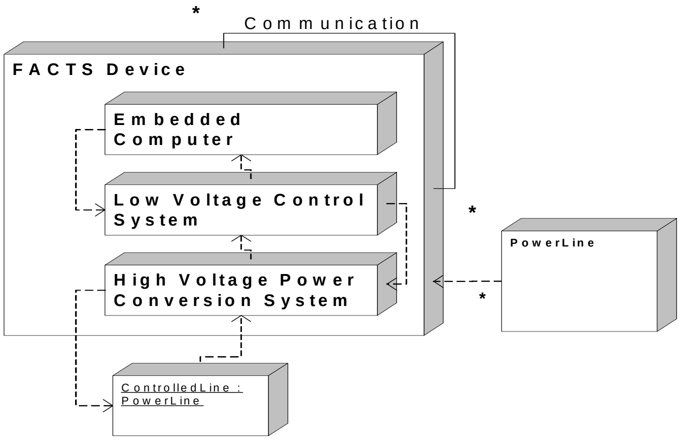

Figure 2. Operational Schematic of a UPFC

A FACTS Device consists of an embedded computer that depends on a low voltage control system for signal processing, which, in turn, depends on a high voltage power conversion system for rapidly switching power into the power line. Each FACTS device controls one power line (ControlledLine) and multiple FACTS devices interact with each other via exchanging messages over network communication. The net effect of the FACTS devices and the power grid is that each power line and FACTS device is affected by other power lines and FACTS devices. Using this idea, the FACTS Power System is modeled by a high level context object diagram that appears in Figure 3. The FACTS Power system is an object acted on by the Service Provider and by a Contingency. All other functionality is encapsulated in the FACTS Power System object. The three attributes on the right of each object are parameters, methods, and constraints. Thus, at this level, the FACTS Power System constraints are to maintain voltage stability, operate without overloads, and maintain availability.

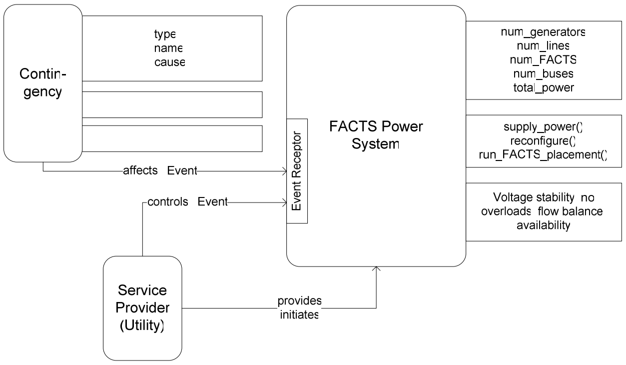

Figure 3. FACTS Power System Context Object Diagram

IV. FACTS PLACEMENT AND DISTRIBUTED CONTROL

Expanding the FACTS Power System object from above shows the relationship between FACTS Device, Placement, and the Power Transmission System (Figure 4). Key is the way the FACTS device interaction with the Power Transmission System. Currently, actual control of the transmission system consists of a patchwork of controls that have evolved over time. Recent work in the *GridStat* [5] system provides a consistent picture of the power system's operation for improved information flow but not control. The FACTS Device acts on and receives data from the Power Transmission System as well as interacts with other FACTS devices.. FACTS devices hold the greatest potential in power flow control. Placement of the FACTS devices is shown as a (Design) component of the FACTS Power System.

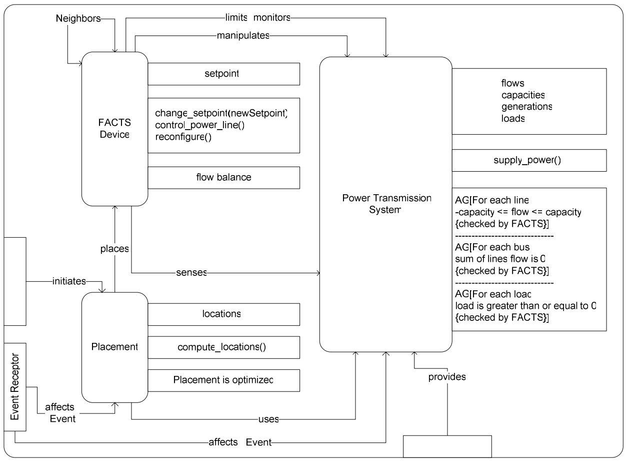

Figure 4. FACTS Power System Object Decomposition

Placement and control are closely related activities. Once the placement is fixed, the control settings of the FACTS devices must be able to change in response to changing network parameters and must be coordinated to maximize performance. Therefore it will ultimately be necessary to consider placement and control in an integrated approach.

Given the expense of installing these devices within the system, it is of utmost importance that the FACTS devices be placed where they have the greatest impact on system operation. This is treated under two frameworks, the *power flow framework* that models the power system as a flow problem, and the *evolutionary algorithm framework* that optimizes placement and constructs an optimal control algorithm. Current work in genetic algorithms [6][7][8] has explored FACTS device settings, but little work to date has examined how to coordinate FACTS devices in real-time to respond to contingencies.

Long-term control and dynamic control are objects embedded in the FACTS device and correspond to two of the three time scales of control discussed in the introduction. Figure 5 depicts the relationship between these two objects; long-term control interacts directly with its neighboring FACTS devices while dynamic control responds only to local line readings and sends control signals to a local DSP.

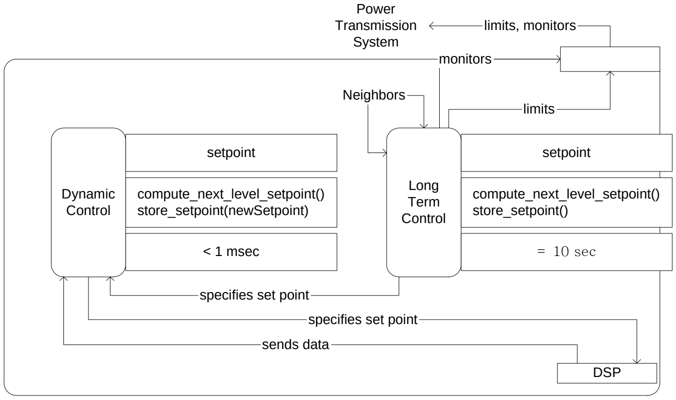

Figure 5. Long-term and dynamic control object relationships within embedded PC. The DSP controls power electronics that control the PowerLine (not shown)

The Power Flow Framework

The *power flow framework* [9] of FACTS device control enables the devices to adjust to changing system topology and loading. In this approach, the power flow in the transmission system is modeled as a directed network flow problem with a directed graph $G(N,A)$ modeling the power. The set of nodes, N, correspond to the buses of the power network. The power flow between nodes is represented by arcs, A, and the direction of the arcs is dictated by the existing power flow. Each arc is assigned a weight, which may denote the maximum power flow allowable over that arc in the network or may reflect economic constraints. Additionally, the physics of the problem as represented by the power flow equations that dictate that power must balance at each system bus.

A power system may be represented as a directed graph in which all power flows from the virtual source (s) to a virtual termination (t). The source is a "virtual source" node connecting all the generators and termination may be considered the network "ground" node. This model is useful in the case when a line is lost due to a contingency and the resulting redirected power flow stresses the network. Too much power may flow over lines of inadequate capacity and one-by-one the lines overload and trip out. A procedure is needed to rapidly rebalance the power flows by directing the power flow across transmission corridors with greater capacity or by shedding load. The redirection of power flow is accomplished by a set of FACTS devices working in a coordinated fashion to maximize the loadability of the system without overloading any lines. This coordination can be accomplished by modeling the redistribution process as the *maximum flow* (max-flow) in a digraph [10]. Algorithms for performing this task may be found in the literature of operations research (such as [11][12]). Conceptually, max-flow algorithms work by successively assigning flows to arcs along a directed path from s to t until no more flow can be added.

When an arc (line) is lost due to a single-line contingency, the arc weight becomes 0. Then the flow in the network from s to t is rebalanced using the same max-flow algorithm on the network. Antiparallel arcs in the graph model allow for bidirectional flow in a power grid. In reconfiguration, flow may reverse direction and use some of these anti-parallel arcs as well as use the forward arcs, but to a lesser capacity. The max-flow algorithm may be implemented in real-time by taking the line capacity as the scheduled power flow (satisfying a load flow solution) for that line. In the event of a contingency, these capacities are the initial capacities for the max-flow algorithm.

Under the power flow framework, the max flow algorithm schedules only real power and, thus, indicates the "ideal" capacity of each line throughout the system under the given system topology and loading profile. While reactive power flow and line losses skew the "ideal" flow through the system slightly, the preliminary results indicated that if the FACTS devices are properly located and set to the max-flow "ideal" setting, that the remaining non-controlled lines of the system are generally within a few percentage of the capacity dictated by the max-flow algorithm [13].

One of the primary research areas impacted by the FACTS research is the distributed real-time control of the interacting FACTS devices. To provide real-time power flow scheduling, the graph theory based strategy is implemented such that it can respond to contingencies in real time over a wide geographic area. Using the communication and computational processes of the FACTS devices along with a network interconnection the max-flow is implemented as a distributed operating control algorithm. This is in contrast with much of the previous work in FACTS power flow control has concentrated on determining *a priori* how power is distributed in the network from each source. The work of [14] traces the flow of power to load by solving nodal flow equations. This idea is further explored in [15] by selectively removing power sources to identify flow in the network. Both these efforts are targeted towards identifying flows for economic reasons, but the same principles can be extended to configuration management. The difference, here, is that the actual flow balance needed to prevent cascading failures is computed in a distributed real-time manner. The configuration control is executed by embedded control devices rather than a static allocation or switching.

The FACTS devices behave autonomously, but they depend on information received from the transmission network to determine their responses. Each FACTS device must continually monitor not only its own behavior in response to system operating changes, but the response of neighboring devices as well. Each FACTS device must be able to determine if another device is out of service and, if so, to compensate for the loss of that device.

While the max-flow algorithm can be run from a central site, there are several problems with this centralized approach. The first is that communication with the central site may be compromised due to hardware failures or intrusions into the communications network. The central site itself may also be subject to failure or subversion. Decentralized, or parallel, algorithms for the solution of max-flow have been proposed by many researchers. In [16], a parallelization using a shared-memory multiprocessor results in nearly linear speedup (performance improves linearly as the number of processors increases). A distributed algorithm is presented by [17] with a time complexity of using a processor at each node. In [5], the investigators developed a distributed max flow algorithm for power flow computation. Recent results have extended this to an implementation of Goldberg and Tarjan's parallel algorithm [18] on a distributed system [19].

FACTS Placement Strategies

While the primary thrust of the proposed work is to develop distributed real-time long-term control algorithms for FACTS devices, the successful operation of these controllers depends significantly on their placement within the transmission network. The optimal placement, however, is, in turn, dependent on the control algorithms.

FACTS devices fall into two primary categories based on their interconnection to the power line. The placement of series devices is considerably different than the placement of shunt devices since series devices impact active power flow more significantly, whereas shunt devices tend to impact voltage magnitudes more significantly. Fairly comprehensive studies have been performed to determine optimal placement of shunt devices [20][21], so the proposed study will concentrate on the placement of series FACTS devices in the bulk power system. A variety of approaches have been proposed for placing series devices in the system, but there is currently no methodology that has been shown to be adequate in both steady-state (power flow) and dynamic operating applications. Further, little comprehensive work exists that dynamically determines the settings of the devices with respect to changes in system topology or loading.

Previous work in determining the optimal location of FACTS devices can be categorized into the sensitivity-based approaches based on variable impedance of the power line, stochastic methods that consider large optimization spaces, and heuristic methods.

Most FACTS placement algorithms have been applied to a system only at steady-state, therefore the control settings of the devices are chosen for a particular topology, load, and generation profile and may also be computationally time-consuming. With the exception of the single contingency sensitivity method [22], these methods also do not consider the placement and setting of the devices over the entire set of possible contingencies ensuring that no lines are overloaded for any loss of line. But this is exactly the FACTS application that is of interest to transmission service providers, the coupling of placement and control that is able to adapt rapidly to changes in loading and generation profiles or line contingency. In [23], the authors described a suboptimal solution to the placement problem that employed a greedy placement algorithm with the max-flow control algorithm described in the previous section. This approach yielded good results for the model IEEE 118 system; nine of the lines were identified as potential sites for FACTS placement. Each contingency was analyzed separately and lines were selected using a heuristic "greedy" approach by choosing those lines first that are chronically overloaded. With FACTS devices placed at these sites and controlled by the max-flow, the system is able to withstand 95% of all single contingencies with no line overloads. Since these FACTS devices are typically placed along major flow corridors, most of the flow throughout the system can be affected. In the remaining 5% of contingencies, the overloads are typically localized. However, further brute-force experiments demonstrated the sub-optimal nature of this approach.

The Evolutionary Algorithm Framework

Evolutionary Algorithms (EAs) have been proposed to place FACTS devices [6][7][8][24][25][26][27]. EAs are a class of stochastic, population-based optimization algorithms inspired by modern evolution theory [28]. The basic evolutionary algorithm in each of these approaches is similar and endeavors to optimize some system characteristic such as available transfer capacity (maximization problem) or system losses (minimization problem). Many of the methods proposed do not use the EA to determine the placement of the devices, but rather, to determine the settings of previously-placed FACTS devices. Two EA approaches, however, do specifically consider the placement of these devices. In [24], the optimal location of a set number of *n* phase shifters is determined by coupling a Genetic Algorithm (GA) with an optimal power flow. In this approach, the initial GA population is selected from all possible combinations of lines on which the *n* phase shifters may be placed. For example, a system that has 124 candidate lines on which to place three phase-shifters will have 310,124 possible combinations. This search space is traversed in a directed stochastic manner by applying genetic operators such as mutation and cross-over to population members, with fitter members having a higher chance of selection, until no better combination of FACTS placement lines is being achieved. In this case, the fitness function is dependent on the cost function of the optimal power flow. In [26], a genetic algorithm was used to determine the placement, setting, and choice of TCSC, phase-shifter, TCVR, or SVC type FACTS. This application used system loadability as the fitness function to maximize. This approach had the advantage that different types of FACTS devices could be used – for example the SVC could be used in places where voltage support was needed, whereas a phase-shifter could be placed where active power regulation was desired.

Our current use of EAs for optimizing placement is reported in [29][30] which presents an EA that significantly outperforms the greedy method for placement. There are two versions. The first uses stochastic optimization to place FACTS devices using the FACTS settings from max flow. In the second version, Sequential Quadratic Programming (SQP) is used to optimize a "PI Metric" [31]

$$PI = \sum_{Contingency} P_{Contingency} \left(\sum_{line} \omega_{line} \left(\frac{S_{line}}{S_{line}^{\max}} \right)^{2n} \right)^{k}$$

where ω_{line} is the relative importance of the line, S_{line} is the amount of power on a given line, $S_{line}^{\max}$ is a specific line capacity and n is a number greater than 0. This metric allows contingencies to be weighted by the probability of their occurring and provides the parameter k to control the distribution of PI values per contingency (i.e., by selecting a value of k larger than 1, placements that cause the same aggregate amount of PI values over all contingencies but are less even in the spread of PI values, will be penalized). From the computed load flow of the system, the fitness value is then calculated as a function of the line overloads aggregated over all single line contingencies.

The SQP is used to find valid power flow settings for UPFCs given specific network configuration that minimizes the PI metric.

The PI metric and EA methods produce better results than the max-flow approach as depicted in Figure 6. However, to determine settings in real-time, the SQP must repeatedly execute a load flow calculation on the system to determine settings. Work is continuing to determine the feasibility of evaluating the PI metric in the Distributed FACTS Power System for purposes of real-time control.

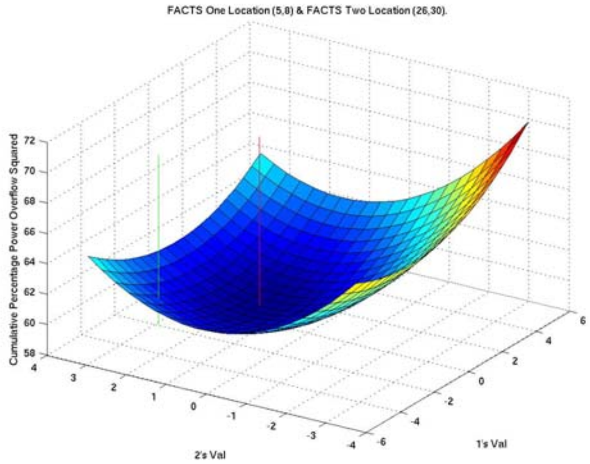

Figure 6. Concavity of PI Metric. The solution at (-2,3) is a suboptimal point chosen by the flow framework.

Within the EA framework for placement, the economic impact can be considered at the system level. This includes analyzing the economic impact on all stakeholders in the system, such as customers, transmission owners, and load-serving entities. Ideally, the device should be placed in a location that will maximize economic benefit while minimizing costs, thereby maximizing the benefit-cost ratio of the social transaction. While benefits (such as lower fees, higher reliability, less downtime) and cost (such as FACTS device installation and operation cost) can often be quantified, a single benefit-cost calculation is often inadequate in capturing the true economic impact on all participants within the systems. Game-theoretic methods can be used in additional to benefit-cost analysis to insure that costs are not simply socialized, but that the market participants who will benefit the most will incur the largest share of the FACTS placement costs [32][33]. A competitive method for allocating cost when used in conjunction with EA techniques can help to achieve this goal.

V. FAULT TOLERANCE AND SECURITY

Critical to the decentralized max-flow are the embedded software/hardware embedded systems aspects of safety, liveness, fault tolerance, information security, and robustness of design/implementation [34]. While the final report of August 2003 Northeast blackout indicated that a software bug was not the cause of the cascading failure, it did indicate that human error in evaluating the software output led to inaction that did contribute [35]. Erratic behavior can be caused by either naturally occurring degradation of service or by intentional (terrorist or hacking) interference as depicted in Figure 7. Since the processors in the FACTS devices and the interconnecting communication network may fail, an approach to ensuring system correctness under all operating conditions must be developed.

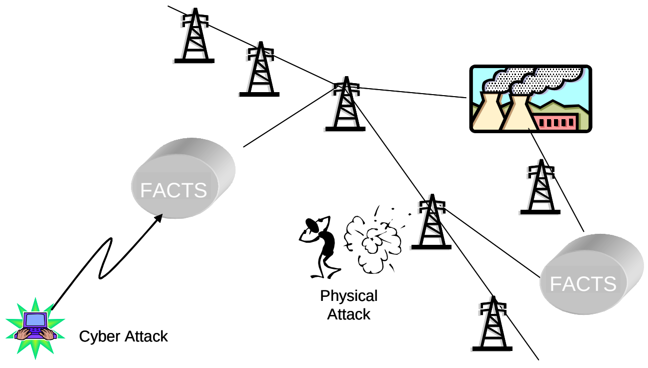

Figure 7. A FACTS decentralized control is subject to many types of failure or attack.

Trustworthiness can be improved by developing fault-tolerant and information secure distributed algorithms [5][23][36] [37][38][39]. In these approaches the mathematical constraints of power system operation, and certain security constraints [40] are embedded in the distributed control algorithms to ensure that the power system meets its operating specifications under contingencies and attacks. These constraints include, but are not limited to:

- Constraint 1: Power flow into a bus = power flow out of a bus
- Constraint 2: Line Power Flow ≤ Maximum Line capacity.

Security is certainly present in the power system and many good observations regarding cyber security policies for the FACTS Power Systems are outlined in [41]. Algorithm design must also take into account non-safety related security constraints regarding information flow, as well.

To accurately check constraints, the state of the system must be distributed across the embedded computers of the FACTS devices in a manner that maintains the current state. Ordering communicated events by logical time provides a consistent picture of a partial order of events across the system [42]. To maintain a consistent cut on this partial order, each message send, message receive, and state variable update is stamped with a Lamport timestamp [16]. The state distribution in the max flow algorithm is based upon the CCSP [43] system for transmitting state variables. In max flow, the constraints use the distributed state variables of capacities of the arcs, the flow of the arcs, and the excess of the vertices. Passing the state variable changes passed at the same time as other communication allows constraints to be checked on a consistent cut of the system. Other approaches for state distribution are epidemic and entropy methods for vector time stamped events [16].

Metrics for the control validation are resistance to cascading failures in the presence of induced contingencies and attacks. Preliminary attack generation studies [19] injected faults of pathological lost messages, corrupted messages, and internal computational errors. Over 97% of these injected errors were detected using the simple definitions of correctness including flow balance and line capacity constraints.

VI. HARDWARE SOFTWARE CO-DESIGN

The FACTS Power System's operation depends strongly on both the hardware and software working together. Design of the architecture prior to software development can put harmful restrictions on the software being developed [45]. In addition, a lack of coordinated interaction between the hardware designers and the software designers can lead to additional problems in the integration and testing of the system. Another possible issue lies with the partitioning of the system into hardware and software components. An early (and fixed) partitioning may not provide the most efficient division of functionality between hardware and software. Modeling the components of the system uniformly as objects allows the eventual decomposition into hardware and software to integrate well.

The object-oriented hardware/software co-design approach was put to use in the creation of the laboratory for the study of FACTS device interactions (FACTS Interaction Laboratory or FIL)[44]. This activity, in itself, requires that the simulation environment correspond closely with the eventual deployed environment of the FACTS Power System. Returning to the object model of Figure 4, the Power Transmission System is decomposed into a series of busses, lines, and generators as shown in Figure 8 or it can be decomposed into a Simulated Power Transmission System in Figure 9. The interfaces to the FACTS Power System are the same between both decompositions. The simulated system runs a real-time time-stepped power system simulation. For each line that contains a FACTS device, it also controls an HIL Line that is a physical laboratory-scale power line whose power flow is set to the power flow resulting from the simulation code.

The developed object model is then used to express data flow and control flow between the objects of the system. This formal specification of the system is used to develop and prove the correctness of the resulting software and hardware elements. In one specific example, the communication interface between the Dynamic Control Object and the DSP was model checked for correctness [33] using RT-SPIN [32].

VII. CONCLUSIONS

This paper presents a comprehensive approach for designing a fault tolerant and robust FACTS power system for mitigating cascading failures caused by successive line overloads. As FACTS devices become increasingly prevalent in the transmission system to control power flows and maintain dynamic security, the development of communication protocols and distributed control paradigms will become paramount to providing reliable electric power.

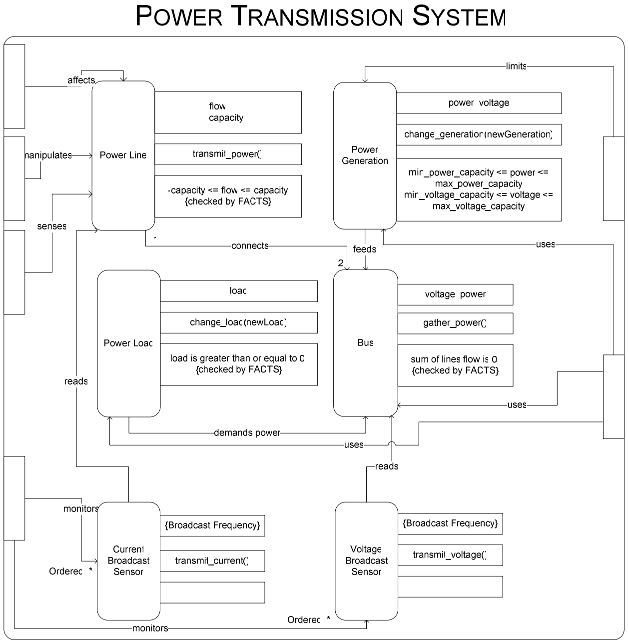

Figure 8. Object Model of Power Transmission System

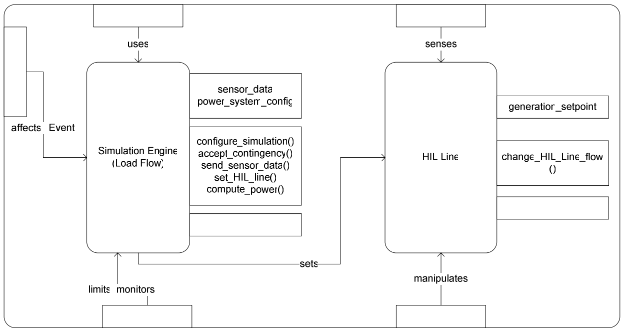

Figure 9. Object Model of Simulated Power Transmission System.

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