

PLANNING RECONFIGURABLE POWER SYSTEM CONTROL FOR TRANSMISSION ENHANCEMENT WITH COST RECOVERY

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ABSTRACT

This project will develop (a) design theory and method for planning hybrid (discrete, continuous) power system controllers, and (b) economic systems, applicable to power system energy markets, for recovering and allocating costs of design and installation of such controllers. Discrete-event system theory and integer programming optimization methods will be used in the control design. The economic thrust will draw on the theory of public economics to determine the level and manner of regulation necessary to provide an appropriate amount of control. The impact of additional control on locational marginal prices will be studied to determine value of the control. These approaches will be illustrated using 3 testbeds, with the most evolved being a 6000 bus model of the western US. A new undergraduate course will be developed that links economics, control, and power systems issues addressed; this course will be accessible to ISU EE and Economics students.

KEY WORDS

Power system, planning, reconfiguration, hybrid control, discrete event system, integer programming, public good economics, locational marginal prices.

1. INTRODUCTION

Future reliability levels of the electric transmission system require proper long-term planning to strengthen and expand transmission capability to accommodate expected transmission usage from normal load growth and increased long-distance power transactions. There are three basic options for strengthening and expanding transmission: (1) build new transmission lines, (2) build new generation at strategic locations, and (3) introduce additional control capability. Although all of these will continue to exist as options, options (1) and (2) have and will continue to become less and less viable. As a result, there is significantly increased potential for application of additional power system control in order to strengthen and expand transmission in the face of growing transmission usage. Incentives for doing so are there is little or no right-of-way, and relative to building new transmission or generation facilities, capital investment is less.

There are 3 types of control technologies that exist today and will continue to be available to power system control engineers: generation controls, power-electronic based transmission controllers, and system protection schemes (SPS). Of these, the first two exert continuous feedback control action; the third exerts discrete open-loop control action. Thus, power system control is hybrid [1,2] in that it consists of continuous and discrete control. Since power systems are already hybrid, and since good solutions may also be hybrid, assessment of control alternatives for expanding transmission must include procedures for gauging cost and effectiveness of hybrid control schemes.

Design of power system control today is done using a combination of linear system theory and time domain simulation. Continuous controllers are located and tuned using linearized methods and checked for robustness using time domain simulation of the nonlinear model. Discrete controllers are designed based on repeated time domain

simulation. The only coordination between continuous and discrete control design occurs via time domain simulation as a check on the proposed design. Such procedures require tedious trial and error analysis of many different operating conditions, and they result in acceptable control design for the conditions and disturbances simulated; but engineers do not know whether they are optimal or even among the better designs, and whether they are robust with respect to conditions and disturbances not simulated.

Planning power systems is performed assuming that the system is required to withstand a certain set of contingencies. A disturbance-performance table exists within the planning standards of the National Electric Reliability Council (NERC) [3] that provides minimum performance specifications for 3 classes of credible events. Class B is comprised of the most likely events – those corresponding to the so-called N-1 contingency. Class C events are perceived to be somewhat less likely but more severe than class B events, e.g., a normally cleared fault on a bus section resulting in outage of more than one component. Performance requirements for classes B and C events are specified in terms of voltage limits, system stability, and no load interruption (for class B) and no uncontrolled load interruption (for class C). Class D events are perceived to be the least likely but most severe class of events and include, for example, loss of all transmission lines on a common right-of-way, or loss of an entire transmission substation. However, there are no performance specifications on class D events, unlike those for classes B and C; mitigation of system impact for class D events is discretionary. Consequently, the industry laments that “these have received minimal consideration” [4]. Yet, the recent concern on *blackouts* and *intentional acts* provides stronger incentive to study Class D events, especially for understanding what kind of additional cost is necessary to provide a system that can withstand them.

Our objective is to develop a unified approach to planning of hybrid controls for reconfigurable power systems. (a) We assume no new transmission equipment (lines, transformers) is installed and generation expansion occurs only at existing generation facilities. This assumption represents the extreme form of the industry trend of relying on control to strengthen/expand transmission capability without building new transmission or strategically siting new generation. (b) We consider design solutions for *each disturbance* based on control, where options are limited to SPS (discrete control) or FACTS-type devices (continuous control), but not both. This identifies problems for which SPS and FACTS are competing alternatives, providing the ability to compare the approaches for effectiveness and cost. (c) The final control design coordinates use of both continuous and discrete controllers. (d) The control design is driven by controller effectiveness, controller cost, the contingency set, and uncertainty in loading conditions/generation availability. (e) The design is performed relative to 2 sets of severe, but credible contingencies. One set is comprised of class-C contingencies; the other set of class-D contingencies. This enables comparison of control cost for maintaining today's system strength against control costs for increasing system strength to withstand the next higher event class. This difference, then, can be considered as a rough cost-estimate associated with a first-level strengthening of power systems to withstand class-D contingencies. (f) We identify organizational issues within the industry associated with proper and adequate *cost recovery* for control design, installation, operation, and maintenance through design of appropriate procedures, an issue that is complicated by the difficulty in identifying the extent that different entities benefit from the control.

Blackout scenarios as observed on August 14, 2003 can be affected by innovations and training in one of 4 areas of power engineering: design, maintenance, operation, and restoration. This work will reduce frequency and mitigate severity of future blackout scenarios by providing an effective means of strengthening transmission systems while avoiding the economic and environmental problems associated with construction of new transmission.

2. TESTBED AND SYSTEM MODEL

We use 3 testbeds of the western US electric power system. One of these is illustrated in Fig. 1, a simplified 4-bus model that reproduces the structural characteristic of the Western Electric Coordinating Council (WECC) system. This system is utilized for conceptual development and initial algorithm testing. Testbed 2 models 179-buses and 29-generators, and is used for more comprehensive algorithm testing. A full planning study will be completed using a 6000 bus model, testbed 3, provided by Bonneville Power Administration. Two disturbances of particular interest to this system are (a) loss of the Pacific DC Intertie (PDCI) and (b) loss of the Pacific AC Intertie (PACI), and

represent class C and class D disturbances, respectively, for which discrete control systems are already designed.

Loss of the PDCI: The PDCI is a 3100 MW DC tie providing a high capacity link between Pacific NW and Los Angeles. Under high north-south power flows, an unmitigated disturbance causing loss of the PDCI has catastrophic impact in terms of voltage collapse in California, resulting in uncontrolled islanding and major load interruption. A discrete-action control scheme mitigates this disturbance according to Table 1.

Loss of the PACI: The PACI is a 4800 MW tie bringing power from Pacific NW to California, operating in parallel with the PDCI. With high north-south power flow, a disturbance causing loss of PACI weakens transmission between source and sink; if not mitigated, it causes out-of-step conditions, uncontrolled islanding, and major load interruption. A discrete-action control scheme mitigates this disturbance according to Table 2.

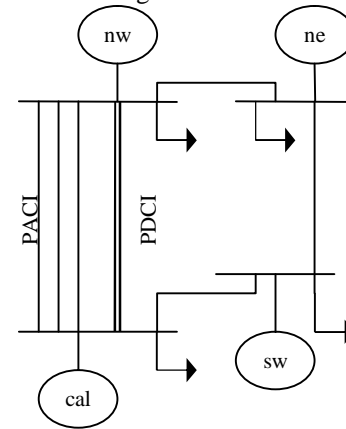


Fig. 1: Testbed model 1 of the US WECC System

Table 1: Discrete action control for loss of the PDCI

#	Disturbance or Action	Timing (cycles)
1	Drop both PDCI poles	0
2	Increase PACI series capacitive compensation	15.5
3	Trip generation in NW	11
4	Switch 400 MVAR shunt capacitor on PACI	15
5	Switch out capacitors at northern end of PDCI	120

Table 2: Discrete action control for loss of the PACI

#	Disturbance or Action	Timing (cycles)
1	Fault PACI	0
2	Local protection operates to clear fault Open all three 500 kV circuits of PACI	4
3	Trip generation in N. Cal and in NW	11
4	Trip Cal pump-storage if pumping	13
5	Insert braking resistor in NW	15
6	Separate into 2 islands Open NW-Cal ties Open East-Cal ties Open SW-Cal ties	15.5
7	Remove braking resistor	43.5

An alternative to both of the above control policies is to make use of controllable series reactance (TCSC, for example) [5] to decrease impedance on both the east and west ties, and, for loss of the PDCI (Table 1), to also make use of controllable shunt reactance (SVC, for example) to increase reactive resources in the southern region.

3. CONTROL DESIGN APPROACH

The control system planning problem for power systems is inherently an optimization problem where, for a specified time interval (e.g., next 10 years), we select control options that minimize costs associated with (1) installation of the control systems selected, (2) each control action taken, and (3) impacts of system disturbances. Rigorous solution to this problem is extremely complex because of three reasons.

First, the solution space is extremely large, since every bus (nodal control) and every circuit (link control) offer possible control locations, and every control location may be either discrete or continuous. We refer to a specific selection of nodal and link control capability as a *control plan*. We refer to a specific sequence of control actions for a given disturbance, available through a specific control plan, as a *control policy*. For example, Tables 1 and 2 above constitute specific control policies for loss of the PDCI and PACI, respectively. Solution complexity is appreciated from the facts that every control plan must stabilize every disturbance, and exhaustive evaluation of a single disturbance for a single control plan requires simulation of that disturbance for every possible control policy (i.e., every possible permutation of discrete control actions). The second reason for solution complexity is that system performance evaluation for candidate solutions is highly computational. The most effective way to evaluate system performance is via load interruption; for a certain disturbance and a specific control action, this requires numerical integration of the differential-algebraic system when there are many thousands of states. The third reason is that uncertainty exists in the identity of disturbances and in the operating conditions that can occur.

We propose procedures for solving the control system planning problem, under the following assumptions: (1) The power system has an existing set of continuous controllers and protections that are represented in the model, including those on existing generators such as generator out-of-step and overspeed relays. (2) Candidate controllers include discrete or continuous control of any real or reactive bus injection or of any bus shunt (nodal controllers) or of any line series reactance (link controllers), and coordinated use of any of these in combination. (3) We utilize the NERC Class-C performance criteria for each disturbance, independent of whether it is class-C or D disturbance. Class-C criteria requires that there be no uncontrolled loss of load or cascading [6]. (4) We confine analysis to problems that result in severe performance degradation, including out-of-step conditions and voltage collapse.

Our proposed hybrid control planning approach requires 4 basic steps: (i) contingency selection, (ii) development of generation/load growth futures, (iii) identification of control policies for discrete-action controller design and continuous controller design, and (iv) development of the control plan. The first two steps are described briefly, with more emphasis placed on the third and fourth steps.

In the first step, 2 sets of contingencies are selected for each testbed system, one set consisting of class C contingencies and the other set consisting of class D contingencies. Thus, for each testbed, we design a class-C control plan and a class-D control plan; economic comparison of these two control plans provides an indication of the alternatives required to provide an increase in transmission resilience to disturbances. This approach is similar to the philosophy articulated by the East-Central Area Reliability Coordination Agreement Regional Reliability Council [7].

In the second step, a limited number of generation/load growth *futures* are identified for each testbed, where each future is characterized by a load growth percentage for each load bus and a generation allocation for each generation bus. For example, one future may assume uniformly increasing load at 5% per year and allocation of that load increase to existing generation (with associated increase in unit reactive capability) based on percentage of total installed capacity. The k^{th} selected future is associated with an estimated probability p_k such that selected futures are assumed to comprise the entire probability space. In order to ensure an adequate number of disturbances to study, we grow the testbed in the direction of each future until all contingencies in both contingency sets result in out-of-step conditions or voltage collapse.

The fundamental problem to be solved in this step is, for a specified contingency and corresponding set of conditions resulting in violation of class-C performance criteria (no uncontrolled loss of load), identify effective and economic controls such that the only interrupted load resulting from the disturbance is planned and controlled. We assume that uncontrolled load interruption occurs for system out-of-step conditions (brought on by machine groups losing synchronism with one another over a weak tie, often characterized by large power swings and interarea oscillations) or voltage instability (fast or slow, brought on by insufficient reactive resources in one or more network regions). We outline the intelligence necessary for algorithmic identification of cost-effective controls to mitigate disturbance impact. Each disturbance is mitigated using either the minimum cost selection of discrete actions *or* the minimum cost selection of continuous controllers that eliminate uncontrolled load loss. We do not use combinations of discrete and continuous controllers for a single disturbance in order to enable comparing cost and effectiveness of the 2 approaches. This does not preclude having both types of solutions in the final control plan because the final control

plan will be developed based on composition of control policies for all disturbances.

3.1 Discrete-action controller design

A hybrid automaton, shown in Fig. 2, is a key concept in our approach to discrete-action controller design. A similar approach was introduced and successfully applied in the design of control strategies for autonomous vehicles [8,9].

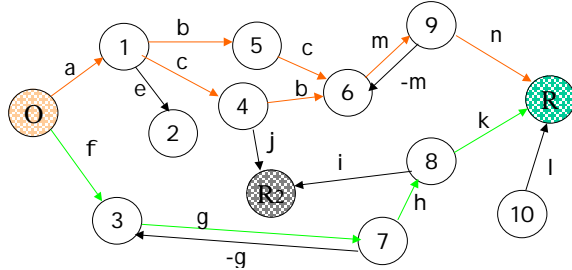


Fig. 2: Hybrid automaton. Recovery node R is reached from Origin node O through several paths. Optimal path is O-3-7-8-R. Node R2 represents another possible but higher cost recovery node.

A hybrid automaton is comprised of nodes and edges. The origin node is the node $O(r)$ resulting from occurrence of fault r . All other nodes in the graph correspond to modes with steady-state equilibrium, characterized as unstable, stable, or stable and safe. We restrict our discussion to the case where all nodes are stable and safe. These are the preferred nodes from a practical point of view. Nonetheless, situations where other types of nodes are present may arise and they can be easily included in our design process. The edges are discrete control actions (maneuvers). A maneuver may be a one-step control action possibly involving many simultaneous switches, or it may represent a sequence of switches. The preferred edges of the automaton are those that are safe, meaning that the transients in continuous variables caused by the switching associated with the edge are within limits, and stable, meaning the node where switching is initiated is within the region of stability of the node resulting from the switch.

A **fault-tolerant reconfigurable control problem statement** is then “how do we control the discrete control variables in response to discrete disturbances (for the fixed continuous controller h) so as to recover from the faults resulting from discrete disturbances.” Three major sub-problems are contained in the design. In subproblem 1, we determine the nodes of the automaton corresponding to stable and unstable equilibria. In subproblem 2, we identify the optimal stable equilibrium among the identified nodes. In subproblem 3, we determine the edges by searching over the automaton graph for the optimal sequence of safe and stable edges, leading to the recovery node. As part of subproblem 3, we identify the optimal sequence of switching to move from the post-disturbance configuration to the optimal stable equilibrium. Some notation follows. The general mathematical model is

$$\dot{\underline{x}} = \underline{f}_z(\underline{x}, \underline{u}), \quad \underline{0} = \underline{g}_z(\underline{x}, \underline{u}), \quad (1)$$

where \underline{x} is the state vector, z is a discrete mode or configuration, and \underline{u} is the control vector given by $\underline{u} = [\underline{y}, \underline{P}, \underline{Y}]$, where \underline{y} contains generator terminal voltages, \underline{P} contains real and reactive bus injections, and \underline{Y} is the network admittance matrix which reflects bus real and reactive shunts, line charging, and line impedances. Discrete controllers operate in such a way so as to modify \underline{f} and \underline{g} by eliminating some of the differential equations and corresponding state variables (generator tripping) or by changing the algebraic equations (through \underline{Y} via shunt or series switching) so as to develop a specific mode z . We also define X to be a set of continuous state variables, U is a set of continuous control variables, Q is a set of discrete control variables such as relay settings, R is a set of discrete disturbance variables such as line-faults, and $Z = Q \times R$ is a set of discrete modes. X and U are finite dimensional vector spaces; Q and R are a finite set. A discrete-mode z is a pair (q, r) , where q is the discrete control mode and r is the discrete disturbance mode. In a discrete mode $z = (q, r)$, the dynamics of the system are given by, $dx/dt = f_z(x, u)$, $0 = g_z(x, u)$. Here, “ f ” and “ g ” are parameterized by the discrete mode z , i.e., each discrete mode has its own continuous dynamics, and its own power flow constraints. Given a continuous control u , for a discrete mode $z = (q, r)$, an equilibrium state is given by the solution of $0 = f_z(x, u); 0 = g_z(x, u)$. We use $Xe(z)$ to denote the set of equilibrium states for discrete mode z . An equilibrium state may or may not be stable. We use $Xse(z)$ to denote a subset of $Xe(z)$ consisting of the stable equilibrium states for discrete mode z . A stable equilibrium state may or may not satisfy the safety constraints given as inequality constraints for the continuous variables of voltages and powers, represented as $h_z(z, u) \geq 0$. We use $Xsse(z)$ to denote the subset of $Xse(z)$ consisting of safe stable equilibrium states for discrete mode z .

A discrete mode z is said to possess an equilibrium if $Xe(z)$ is nonempty; z is said to be stable if $Xse(z)$ is nonempty; and z is said to be safe and stable if $Xsse(z)$ is nonempty. For each node r , we use $Ze(r)$, $Zse(r)$, and $Zsse(r)$, respectively to denote subsets of discrete mode set Z that possess an equilibrium, are stable, and are safe and stable, respectively. The set $Zsse(r)$ is the set of discrete modes in which the system may transition into when the discrete disturbance is r . In order to select a specific discrete mode from among the ones in $Zsse(r)$, an optimality criterion is used. A discrete mode in $Zsse(r)$ is optimum if it minimizes the power loss to loads. Let the optimum be $zopt(r)$, which obviously belongs to $Zsse(r)$. $zopt(r) = (qopt(r), r)$ is called the “recovery mode” for r .

A hybrid automaton is associated with each fault r . The nodes of the automaton correspond to the steady state equilibria, $Ze(r)$. The edges, one-step discrete control actions, called maneuvers, consisting of a set of switches occurring at the same time, are denoted by $E(r)$. A subset of these edges is between a pair of nodes that are stable (the parent node of the edge is in the region of stability of the child node of the edge), i.e., belonging to $Zse(r)$. We

call them stable edges and denote them by $Es(r)$. A further subset of $Es(r)$ is also safe, meaning the transients in continuous variables caused by the one-step switching associated with such an edge lies within the safety limits of voltage magnitudes and power flows. Denote this set of safe and stable edges by $Ess(r)$.

Subproblem 1 (identify stable and unstable equilibria):

There are 2 steps to this subproblem: step 1 searches for acceptable solutions based on switching of impedance elements; step 2 finds acceptable islanding solutions.

Step 1: We assume candidate switching locations include all buses (for switching shunt elements) and all lines (for switching series elements). It is generally possible to limit candidate switching locations based on the location of the disturbance and characteristics of the post-disturbance system. The amount of impedance available to switch in as shunt and series elements are specified based on engineering judgment. The problem is to label each possible configuration resulting from a switch as stable or unstable. For N possible switching actions, we have 2^N equilibria to assess. The assessment is performed using a continuation power flow calculation [10] to obtain loadability; the performance index is then L , the amount by which load exceeds loadability. $L > 0$ indicates the equilibrium is unstable and gives the amount of required load interruption; $L < 0$ indicates the equilibrium is stable. A practical consideration provides that we may eliminate equilibria that have more switching than is necessary to achieve stability and acceptable performance. Thus, we proceed by first assessing all equilibria with 1 switching, then all equilibria with 2 switchings, etc., until we find a switching that is stable and acceptable (no load interruption). It is possible to complete such an assessment in a reasonable time only by using fast screening [11,12] from continuation methods; these methods conveniently estimate loadability for stable and unstable equilibria to use for the performance index L . Alternatively, boundary tracing methods [13] provide accurate and fast solutions.

Step 2: It is generally the case that islanding necessarily results in controlled loss of load, so step 1 solutions, if obtainable, are generally preferable. Yet, there may be disturbances having step 1 solutions that also result in load loss; in this case, it is conceivable that an islanding solution could be preferable if it resulted in less load loss. In step 2, the system is separated into islands. The method is used together with a load shedding scheme based on the rate of frequency decline [14]. We employ a 2-time-scale method [15] to identify coherent generator groups, implemented by running EPRI reduction software [16] and an automatic islanding algorithm that utilizes network structure in terms of the adjacent link table data [17] together with bus P and Q injections. Interface buses between coherent groups are identified, and a reduced subnetwork is formed. In this subnetwork an exhaustive search is made to ascertain whether islands can be formed between coherent groups. If not, then we move loosely coherent machines from one group to the other and repeat

the process. Once appropriate islands are found, the load-generation balance in each island combination is determined. The island combination that has the least load-generation imbalance is chosen.

Subproblem 2 (Identify optimal stable equilibrium): An optimal stable equilibrium node can be found by selecting the node for which the performance index (load loss and installation cost) is minimum from among the nodes that were found in subproblem 1. Alternatively, we can attempt the following integer-optimization that does not restrict the search over the nodes found in subproblem 1.

$$\min_{q \in Q} n \text{InterruptCost}(L(z = (q, r))) + \text{InstallCost}(q)$$

$$\text{subject to: } \underline{0} = \underline{g}_z(x, \underline{u}) = \underline{f}_z(x, \underline{u}) \quad (2)$$

where the first term gives load interruption cost over the planning period (n times the load interruption cost per disturbance where n is the expected number of times the disturbance occurs over the planning period), and the second term gives the install cost associated with the discrete switches utilized in the control policy for this disturbance. L , the performance index, as described in subproblem 1, depends through the loadability on the discrete mode z as determined by the disturbance r and the discrete switching actions q . The equality constraint is the power flow equations for discrete mode z determined by the disturbance r and discrete switching actions q through the admittance matrix \underline{Y} , a part of \underline{u} . Assuming that InterruptCost increases linearly from the origin with increasing L (or increasing interruption), i.e., $\text{InterruptCost} = cL$, then the objective function can be written as $\min_{q \in Q} L(z = (q, r)) + I \times \text{InstallCost}(q)$

where $I = I/nc$ and c is the cost per unit interruption. Thus, we see that our problem is to minimize load interruption together with the discrete switch install cost scaled by I . Introducing additional notation, let k_j = number of capacitive segments switched in at the j^{th} node (or link) and C_j is the installation cost per segment at the j^{th} node (or link). Then q is defined by the selected nodal and link switch values k_j . The install cost of the switches is the summation over nodes and links of the cost of each switch; our problem is now:

$$\min_{q \in Q} L(z = (q, r)) + I \times \left(\sum_{j \in \text{Nodes}} C_j k_j + \sum_{j \in \text{Links}} C_j k_j \right)$$

$$\text{subject to: } \underline{0} = \underline{g}_z(x, \underline{u}) = \underline{f}_z(x, \underline{u}) \quad (3)$$

Inequality constraints on generation level, line loading, and bus voltage magnitude may also be included. One may solve this problem for different values of I in order to obtain different stable and acceptable discrete switching modes q , where each q is comprised of a combination of different series and shunt switched elements, and the different modes reflect different tradeoffs between effectiveness (through L) and install cost. Alternatively, one may remove the install cost from the objective function and including it as an upper-bounded inequality

constraint, and then obtaining different solutions for different upper bounds on install cost. Here, we limit the set of controllable buses and lines to a set chosen a-priori based on the nature of the problem resulting from the disturbance. This problem, as posed, is a mixed integer nonlinear optimization problem where the decision variables are the switch values together with the generator bus power injections; we will utilize appropriate optimization techniques to solve it [18, 19].

Subproblem 3 (Identify optimal switching sequence):

The system initially operates in a discrete mode $z00 = (q0, r0)$ that belongs to $Zsse$. A discrete disturbance changes the discrete mode to $z0j = (q0, rj)$, called the origin mode. A fault is said to have occurred if $z0j$ belongs to $Z - Zsse(rj)$. Knowing the state $z0j = (q0, rj)$ resulting from a fault rj , we need to compute a sequence of switchings to steer the discrete control mode from the origin $z0j$ to the recovery mode $zopt(rj) = (qopt(rj), rj)$.

The preference will be to transition from the origin node to the recovery node using a sequence of safe and stable edges in $Ess(rj)$. The safety of a stable edge can be checked via time-domain simulation and using formal verification methods for hybrid systems [20,21] when they apply. For simplicity, we first assume that there is a path of safe and stable edges.

Optimal switching sequence within the automaton: The likelihood of finding paths from the origin node to recovery node increases with the number of nodes in the graph, which, in turn, increases the verification effort in searching for safe and stable edges. If the hybrid automaton is rich enough, there may exist several safe paths connecting the two nodes. These will correspond to different feasible switching sequences. We assume there is cost associated with any edge and any node in the automaton. For example, part of the cost could be given by the time to hop from one node to the next. In searching for these paths, we could first search for all paths connecting the origin and the recovery nodes, and then order them according to their cost. Another approach is to do both operations at the same time using dynamic programming [22]. The search algorithm starts from the recovery node. According to the cost function used, there may be policies with smaller cost requiring more steps to reach the recovery node. In such cases, the algorithm should continue searching for optimal policies made of more than N maneuvers. It is possible to compute the length of the longest (non cyclic) path. Such length will cap the number of steps needed for the algorithm to terminate. The result will be a list of optimal paths connecting origin and recovery nodes indexed by the length or the number of maneuvers that they require, from which the absolute optimal path can be easily picked.

The search restricted to the safe and stable subgraph may be too restrictive in the sense that the origin and recovery nodes may not be connected by a sequence of safe and stable edges. One can allow for transient nodes representing unstable nodes and unsafe transitions.

Clearly, moderately unstable nodes are preferable to highly unstable ones essentially because of their longer time constants, which allow the control system with more time to react. The search for the optimal path should also impose the constraint to spend minimum time at the unstable transient nodes. Also when one or more unstable nodes are chained between two stable ones, one should optimize the sequence of events (switchings) in the chain separately, and then replace the whole chain with a more complex maneuver connecting them to stable end nodes of the chain. Although the optimization of events in a chain of unstable nodes is a mixed integer-programming problem [23,24], its complexity should be manageable especially if the number of unstable nodes is small, moreover, sub-optimal or approximate solutions could be more easily computed using neuro-dynamic programming or other aggregation methods [25].

3.2 Continuous controller design

The problem here is to identify, first, whether to use a nodal controller (SVC) or a link controller (TCSC), and second, to determine the controller location *and* the controller actuating signal. Continuous control provides the capability to effectively address out-of-step conditions while simultaneously providing rapid control of voltages. Recent investigations [26] and [27] have developed analytical techniques to determine the optimum location of such devices [28, Chapter 4, 26, 27]. In addition to the location of the controllers, the choice of the input control signal is critical in determining the performance of the supplementary controllers. Residue based observability indices can be effectively used to determine the ideal choice of signals [28, **Error! Bookmark not defined.**]. Given the ranking, together with cost information, we proceed down the ranking, adding a single properly tuned controller having enough control capability to satisfy performance requirements for the given disturbance. A final step reviews all controller capabilities, locations, and input signals for identification of whether a single controller is capable of satisfying performance requirements for more than 1 disturbance.

3.3 Control plan design

The problem here utilizes information obtained in the previous approaches, consisting of (a) set of generation/load growth futures $f=1, \dots, N_f$, with associated probabilities p_f ; (b) set of credible, but extreme disturbances $d=1, \dots, N_d$, with associated probabilities p_d , such that each disturbance, without additional investment, results in uncontrolled load interruption, (c) for each future, and for each disturbance, we have 2 solutions: one is based on discrete actions q_{fd} , and another based on continuous controllers w_{fd} (with each being the minimal cost control solution for future f , disturbance d). The problem is to identify a control plan for the planning horizon T . There are 2 types of approaches to this problem.

The first is to minimize the total installation cost of control subject to stabilization of all contingencies. The second is to maximize control effectiveness subject to a cost constraint. We use the second one since it has a more practical flavor (economic resources are always limited in some fashion). We describe a heuristic approach to solving this problem based on solution to 3 subproblems. We will attempt to consolidate this heuristic into a single (or a series of) mathematical programming problems.

Subproblem A1: *Develop a control plan based only on discrete control.* Our approach here is to identify an expected effectiveness measure E_k for each discrete switch k , and then to select the switches that maximize the summation of the E_k under the budget constraint. The expected effectiveness measure is, for a given disturbance d under future f , the probabilistic expectation of the amount of load interrupted using policy q_{df} but without switch k . We obtain E_k as the sum of load interruption over all disturbances in the disturbance set when switch k is disabled, weighted by the product of the future probability and the disturbance probability. Ranking the switches based on their E_k , we form the discrete control plan based on inclusion of as many top-ranked switches as allowable under the budget constraint. This approach recognizes that the same switch may be used in multiple control policies.

Subproblem A2: *Develop a control plan based only on continuous control.* This is done by ranking the controllers based on an expected effectiveness index similar to that described in subproblem A1. Then we accept, and include in the model of each future, the top-ranked controller, and repeat the effectiveness index calculation for all remaining controllers, accepting, and modeling, the top-ranked controller each time, until exceeding the budget constraint.

Subproblem B: *Devise a single integrated control plan utilizing both discrete and continuous controllers.* Comparison of the discrete control plan of subproblem A1 to the continuous control plan of subproblem A2 reveals useful information about the relative merits and costs of the two types of control. In addition, information obtained in subproblems A1 and A2 are useful in solving this subproblem. For example, a simple approach would take the least-cost control plan, or the most effective control plan, between the discrete and the continuous, but this approach does not recognize that we may achieve lower cost or more effectiveness by combining the two in some way. One way to search for the best combination of the two is to rank the switches together with the continuous controllers based on a ratio of expected effectiveness to cost, and then select the switch or controller in rank order until the budget constraint is exceeded.

4. COST RECOVERY SYSTEMS

The objective to this phase of the work is to develop an economic system to ensure adequate investment in transmission. The work is divided into two phases. Our work in Phase A will focus on necessary foundations. We will first identify the *economic attributes of transmission*

in terms of the basic attributes of market commodities and of public goods. Next we will study existing industry solutions, for other “transportation” industries, (e.g. gas, telecommunications), the most functional US electricity markets (PJM, NY, NE), and the most functional electricity markets in other countries (UK, NZ, Europe). Phase A will conclude by developing a model [29] of the money flow for at least one existing and functional electricity market (PJM).

Our work in Phase B will consider three alternative systems to facilitate transmission investment. The three systems will be developed using information obtained from Phase A. These three systems will include a *public good system* whereby transmission and distribution is in one organization, and the organization purchases energy from suppliers and sells it to consumers, with a regulated surcharge to recover cost of transmission investments. A *performance-based system* whereby transmission is in one organization, without distribution; it has no energy selling or buying interests or needs. It is purely an energy transportation company that obtains its revenues from the transmission service it provides to wholesale suppliers and buyers. The transmission service rates are in terms of usage. These rates are determined each year as a function of the transmission system performance in the previous year, where performance is measured in terms of, for example, total outage duration. A third system to be considered will be the *commodity system* whereby transmission enhancements are developed and offered to a centralized analysis authority whereby they are graded based on the economic criteria (benefit to the real-time market) and reliability criteria (risk reduction for rare events). Here, we will study LMPs in relation to the transmission enhancement needs.

5. COURSE DEVELOPMENT

We will develop a new undergraduate course based on this work, titled *EE/Econ 458: Economic systems for planning in electric power*. Students completing this course will be able to conduct studies in policy, economics, and engineering associated with transmission expansion of electric power systems and will significantly enhance their skills in using optimization methods for engineering and economic problem-solving. Central to the course will be methods of cost-recovery systems for transmission enhancement. A topical outline of this course includes (1) Evolutionary history of the electric industry and present industry structure; (2) Power system operation; (3) Electricity markets; (4) Power system planning and cost-effective solutions; (5) Cost recovery for transmission reinforcements and basics of public good economics; (6) Tariff-based cost-recovery model; (7) Market-driven cost-recovery model; (8) Tax treatment of transmission investments.

6. CONCLUSION

Consensus has it that identification of transmission enhancements and their cost allocation is the most significant problem facing the electric power industry today. It is both a technological problem and an organizational/economic problem. It is technological in two ways. First, the traditional approach of building new transmission meets significant environmental and economic limitations that make it untenable today, and so we must look for novel control methods capable of maintaining equivalent transmission strength. Second, the very real threat of blackouts, as witnessed on August 14, 2003, underscores the dependence of national economic health on transmission grid integrity. It is organizational/economic in that there is presently no clear method of performing the investment allocation. The work described in this paper will address these issues.

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