IMPROVING GRID FAULT TOLERANCE BY OPTIMAL CONTROL OF FACTS DEVICES

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ABSTRACT

One of the most promising applications of the family of power electronic devices called Flexible AC Transmission System devices is to better regulate power flow in transmission grids. In particular, the Unified Power Flow Controller (UPFC) is the best choice for complete power flow control. By selecting proper installation locations and control techniques, UPFCs may be able to prevent the "domino effect," where a single fault leads to a widespread blackout. Due to installation costs, it is hoped that only a small number of devices will be needed to effectively regulate a large grid, however, selecting the optimal number of devices, identifying the best possible installation locations, and finding a technique for coordinated control of these device are still active areas of research. In this paper we provide empirical evidence that common optimization techniques may be used to identify control settings for UPFCs. The evidence indicates that the optimization techniques lend themselves to real-time use, as well as use during the planning phase to identify the best possible installation locations for UPFCs.

Index Terms: UPFC, FACTS, Gradient Descent, SQP

I. INTRODUCTION

In recent years, expansion of national power grids has been hampered by social, environmental, and economic constraints. During the same period of time, power demand has dramatically increased. This combination of increased demand and limited physical expansion, which is expected to continue for the foreseeable future, forces many components of the grid to operate at, or near, their operational limits. Since the power grid is essentially a free-flow network, when a power line fails, the power which it was carrying will be redirected through other lines in the system. This may push the other lines past their operational capacity and may cause them to be disabled, either due to physical failure or by protective equipment. This second round of failures only exacerbates the problem and may lead to a "domino effect," known as a cascading failure, causing a widespread blackout like the 2003 blackout that affected large portions of north-eastern North America. In a May 2002 report to the President of the United States [1], the Department of Energy referred to the over-burdened components as bottlenecks and provided a succinct summary of the significance of the problem:

> Our transmission infrastructure is at the heart of our economic well-being. Imagine an interstate highway system without storage depots or warehouses, where traffic congestion would mean not just a loss of time in delivering a commodity, but a loss of the commodity itself. This is the nature of the transmission infrastructure. That is why bottlenecks are so important to remove and why an efficient transmission infrastructure is so important to maintain and develop.

In addition to the increased congestion on the network, recent deregulation efforts have also introduced control problems. When power was strictly regulated and a single company controlled all three layers of the power system hierarchy (the generators, the long-distance transmission lines, and the local distribution systems), there was incentive to sacrifice efficiency at one level in order to improve efficiency and stability at another. Since deregulation, companies no longer have as much economic incentive to ensure stable power delivery. This is especially complicated in the transmission network where interconnected entities are responsible for power transfers that cannot be strictly controlled. Any transfer of power between two entities will inevitably lead to unwanted parallel loop flows through other parts of the grid which may substantially degrade the stability of a third party [2], [3].

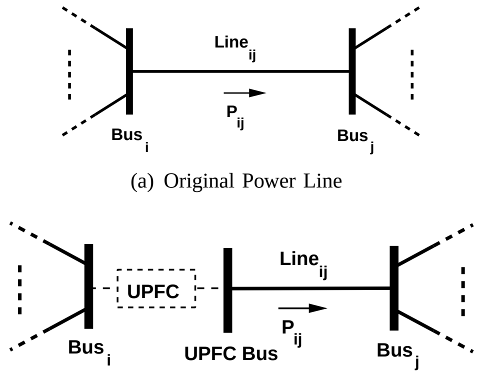
All these problems are, in part, due to the free-flow nature of the power transmission grid: for the most part, power flows through the grid along the path of least resistance (Ohm's law). Most power systems contain elements that help regulate power flow such as phase changers, series compensation, and shunt compensation, but historically these devices were mechanically switched and may not be capable of reacting fast enough to prevent cascading failures. The need for better high-speed control of power flow led to an initiative at the Electric Power Research Institute to develop power-electronic based devices, employing high speed, high power semi-conductor technology, to help better regulate power flow. All these devices are collectively known as Flexible AC Transmission System (FACTS) devices. The family of FACTS devices includes high speed versions of traditional devices like phase changers, and series and shunt compensators, as well as devices based on a new technology, the voltage source converter (VSC). The most powerful of the VSC based devices is the Unified Power Flow Controller (UPFC). The UPFC can be attached between a bus and a power line to help control the phase angle, bus voltage, and line reactance. Because it can control each of these, the UPFC provides the most complete power flow control of any of the FACTS devices [3].

Effective economical use of UPFCs depends on minimizing the installation costs (essentially minimizing the number of UPFCs), while selecting installation locations that maximize system performance. In addition, a suitable control algorithm must be selected to ensure that multiple UPFCs are able to work cooperatively. These are interrelated problems — in order to select optimal locations, the control technique must be known a priori. The work presented here is primarily concerned with improving grid fault tolerance via UPFC control, so the goal of the control algorithm is to redirect power flow from the most overtaxed lines to under utilized lines.

To date, numerous control techniques have been proposed. Most of these fall into two categories: either they are primarily used for short term control of system dynamics or they are intended for long term (steady state) control of power flow. Generally these techniques can be used in conjunction, where the long term control identifies a set point for the steady state power flow and the short term control is used to maintain dynamic stability of the system about the set point and provide additional dampening for transients. Here we present empirical evidence that a common optimization technique may be acceptable for identifying long term set points that maximize fault tolerance by better distribution of power flow. These set points may then be used to help evaluate different potential installation locations. In addition, the evidence indicates that these techniques may be suitable for controlling the UPFCs on-line.

II. System Model

The power grid can be represented as a set of buses interconnected with lines of known series impedance. Each line also has a maximum rated power capacity ($Smax_{ij}$ for the line from Bus_i to Bus_j). Each bus in the system is associated with four state variables: real power, reactive power, voltage, and phase angle. At each bus, two of these variables have specified values and the other two are unknown (which are known and which are unknown depends on whether it is directly connected to a generator). The most common way to solve for



(a) Original Power Line

(b) Virtual FACTS Device Inserted

Fig. 1. Original Line Model and Modifications for simulated UPFC

the unknowns, which was used here, is the Newton-Raphson technique of computing load flow [4]. Once the unknown bus values are computed, line flows can be easily computed as well.

The UPFC's function in this work is to act as a means of forcing a specific amount of real power to flow through a line which causes the remaining lines in the system to adjust their power flow according to the physics of the system. The UPFC was modeled as a mechanism which delivered real power to one of the power line's buses and drew a corresponding amount of real power from the other bus. Fig. 1(a) shows the original configuration of a line from Bus_i to Bus_j and Fig. 1(b) shows the representation of the same bus after a virtual UPFC has been inserted on Bus_i's side. In this case, the UPFC is assumed to be able to increase or decrease the real power flow through $Line_{ij}$ by 20% of the line capacity, $Smax_{ij}$. This is simulated by inserting a phantom UPFC bus and injecting the line's original power flow and the UPFC's modification of it ($\pm$20% of $Smax_{ij}$) into Bus_j. A corresponding amount of power is deducted from Bus_i. Reactive power flow is maintained at the level present in the original system in a similar manner [5].

III. Optimization and Goals

The system performance can be measured against a number of factors, such as:

1) Number of lines with a power flow exceeding capacity

2) Number of lines with dangerously excessive power flow (20% or more over capacity)

3) Aggregate amount of power exceeding line capacities

Our goal is to mitigate the dangerously loaded lines that may lead to cascading failures, which can be achieved by balancing the overall power flow through the system, which minimizes line losses as well. Thus we chose a fitness measure based on each line's percentage of its maximum capacity:

$$\sum_{lines}\left(w_{ij}\frac{S_{ij}}{Smax_{ij}}\right)^{2n} \quad (1)$$

This equation is based on a similar overload performance index used for ranking contingency severity [6]. This particular metric has a high penalty for lines that are at or over their capacity (when the fraction is one or more). By varying n, the amount of disparity between overloads and near-overloads can also be adjusted, however all work presented here assumes that $n = 1$. A weighting factor, w_{ij}, can be used to rank the relative importance of different lines, but here we assume that all lines are of equal importance ($\forall i, j \; w_{ij} = 1$).

This measure was chosen for several reasons:

1) $|S_{ij}|$, the magnitude of the line's apparent power flow, reflects the current and voltage through the line, and hence the primary factor in thermal line failure.

2) It directly reflects the real control criteria — to evenly distribute power flow throughout the system. Better distribution of power flow leads to a lower score.

3) It is a continuous, scalar function in terms of the control variables, which allows the use of efficient gradient based search techniques.

IV. Optimization Procedure

The goal of optimization was to find valid power flow settings for UPFCs in a specific network configuration that minimizes the objective function being used (Eq. 1). As mentioned previously, the UPFCs were only allowed to modify power flow by up to $\pm 20\%$ of $Smax_{ij}$, which represents the only optimization constraint. Any one of numerous constrained optimization techniques could be used, but we chose a relatively common form of sequential quadratic programming (SQP). The form of SQP used the following procedure:

1) Select a uniform random start point

2) Create a quadratic approximation of the search space using the BFGS method [7]

3) Determine the direction of steepest descent. If a local optimum or the maximum number of iterations is reached, stop

4) Use a line search technique until no longer able to "descend"

5) Update the quadratic approximation based on BFGS and go to step 3

Essentially a quadratic approximation is used to represent the objective function in terms of the control variables, then line search is used to find a local optima in a straight line. The quadratic approximation and search direction are updated and the process is repeated until a minimum is found. It is important to note that SQP methods are guaranteed to find a global optimum in super-linear time if the objective function is convex.

This is a sequential, iterative approach to optimization as opposed to using conventional Optimal Power Flow (OPF). OPF techniques would simultaneously solve for bus voltages, phase angles, UPFC control values, and constraints. The SQP approach here sequentially computes the UPFC control values based on objective function computations which compute the bus voltages and phase angles [8].

V. Experiments

All experiments were run on the IEEE 118 bus test system [1]. Since the objective of UPFC installation was to augment power flow and relieve network congestion, a heavily loaded system configuration was used (available upon request).

A. UPFC Impact on System

The first set of experiments was to determine the overall impact of a UPFC on a power grid. It was expected that a UPFC only effects a relatively small region of the power grid. This hypothesis was tested by placing a single UPFC in each of the possible installation locations and setting it to each of its limits ($+20\%$ and -20% of $Smax_{ij}$), then measuring the change in power flow through each other line in the system. In extensive experimentation intermediate values never exceeded those achieved at the boundaries, so the results achieved here can be considered representative, however there is no conclusive evidence that UPFC boundary values are guaranteed to correspond to line flow extrema. The results of this test are presented in Table I.

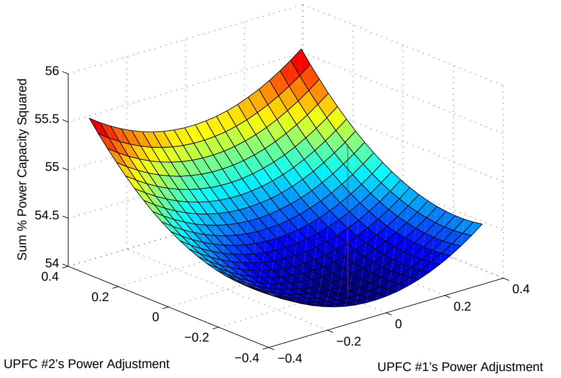
% Dev of S	Max Lines Affected	Mean Affected	Std Dev
$> 1\%$	122	27.93	20.40
$> 5\%$	71	10.97	11.14
$> 10\%$	39	6.54	7.27
$> 15\%$	31	4.81	5.47
$> 20\%$	29	3.80	4.53
$> 25\%$	26	3.10	3.86

TABLE I

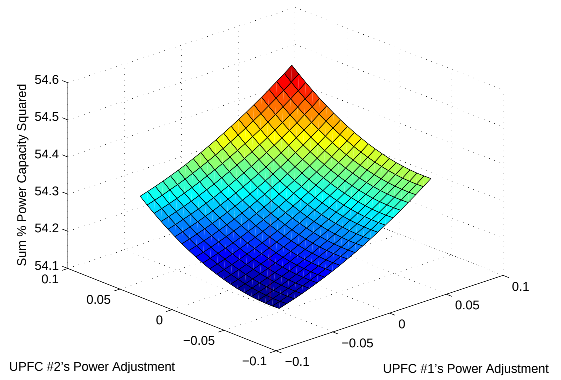
Line Affects for all possible UPFC placements

Note that typically fewer than 30 lines are even slightly impacted by the UPFC. Even in the worst case, only 122 of 186 lines are effected. This indicates that a complete

[1] http://www.ee.washington.edu/research/pstca/pf118/pg_tca118bus.htm



(a) Example of the effects on the objective function of UPFCs installed on lines 27 and 110



(b) Example of effects on the objective function of UPFCs installed on lines 5 and 54

Fig. 2. Examples of the state space for two different UPFC installation locations; vertical lines indicate the optimal settings

load flow may not be necessary to determine the effect of a UPFC — instead it is possible to perform a load flow of only the buses which could be significantly effected by changing the UPFC's settings. If true, this reduces the complexity of the load flow computation which will be beneficial for any optimization techniques that depend on load flow computation.

B. Performance Metric State Space

The second set of experiments was a test of the state space of the objective function being used (Eq. 1). In each of these tests, two UPFCs were installed at random locations and a graph of the objective function was generated for all combinations of UPFC settings. Each UPFC was assumed to have 20 different control points in between its maximum and minimum value.

Fig. 2(a) and Fig. 2(b) show some typical examples of the state space of the objective function. As can be seen, the space seems to be "well behaved" and, consequently, a good candidate for SQP.

Although these results are promising, having more than two devices will lead to more complex search spaces which may have local minima. In order to test for multiple minima, Monte-Carlo style sampling was used. In these tests multiple UPFCs were randomly placed in the system and SQP was performed using randomly chosen start points. If only a single optimum is present, then the algorithm should always converge to it. The system was tested with N UPFC devices where N was either 3, 5, 7, 9, 11, 13, 15, or 17. For each N, 100 different system configurations were randomly generated. Each system configuration was searched from 11 random starting points to try to find evidence of multiple minima. Each FACTS device was assumed to have 100 possible set points. The minimum step size of any of the UPFCs was used as the convergence criteria for SQP. Any solutions that had a Euclidean distance less than twice the mean step size were assumed to be equal (i.e., most of the FACTS devices are set at essentially the same setting). Using these criteria, all the minima found in each system were identical. Although this is not conclusive, it does provide a strong indication that with the given system and objective function, there are only global optima.

C. Real Time Control Issues

The use of SQP for real time control is heavily dependent on both the number of independent variables and the computational complexity of the objective function. In this case, each UPFC's control is an independent variable and the objective function is based on load flow computation. As has been previously mentioned, it is possible to lower the complexity of the load flow computation by only computing the load flow for the part of the system affected by the UPFCs [9]. This indicates that this technique may scale well to larger systems and, if the influence of multiple UPFCs mostly follows the law of superposition, then even multiple UPFC installations may benefit from reduced computation.

A second consideration is the number of load flows that must be computed. Since SQP uses a quadratic model of the objective function in terms of the control variables, it must perform repeated load flows to build and update this estimate. Fig. 3 shows the number of load flow calculations that were required for 100 random placements of 3, 5, 7, 9, 11, 15, or 17 devices. Since both the number and complexity of load flows seems to be bounded for any given size installation, it seems likely that SQP based minimization can be used in real time to ensure that at least a local minima is achieved.

The non-optimized version of load flow used here typically completed within 30ms on a 2GHz Pentium IV. This indicates that even for 17 UPFCs, the optimal long term settings could be found in under 15ms.

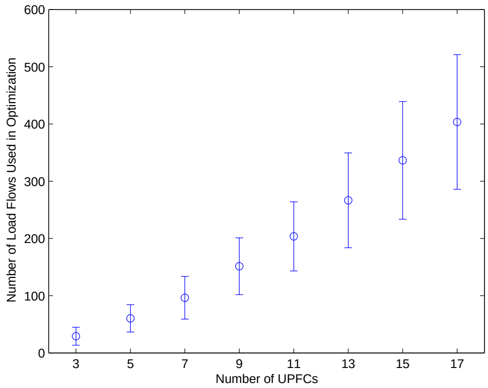


Fig. 3. Number of Load Flow calls used per optimization vs. number of UPFCs; central point is the mean and the error bars include the 95 percentile of 100 random samples

D. SQP vs. MaxFlow

An alternative version of UPFC control, utilizing a graph theory algorithm known as Max Flow, has been proposed [10], [11]. The MaxFlow algorithm was proposed to determine the maximum amount of "flow" between two points in a graph, where each arc of the graph has a maximum capacity. As applied to power systems, Max Flow can be used to determine the amount of power that can flow through each line without causing lines to exceed their capacity.

Although both MaxFlow and the technique presented here have their respective merits, the work presented here shows a substantial reduction in system stress. Generally SQP reduced the severity and number of overloaded lines more substantially than MaxFlow.

In order to compare the two systems, a test system was developed for each possible UPFC installation location. Each of these test cases was then sequentially subjected to all possible single line contingencies and the number and severity of overloaded lines were determined. A summary of the results, which can be seen in Tables II and III, indicate that SQP is better at reducing system stress. Table IV provides a summary of the pros and cons of each technique.

	Total Overloads	Overloads $> 10\%$	Overloads $> 20\%$
Maximum	26	19	14
Mean	0.6611	0.4585	0.3502
Std Dev	1.5928	1.2999	1.0722

TABLE II
SUMMARY OF SQP CONTROL FOR EACH POSSIBLE UPFC PLACEMENT AND EACH SINGLE LINE CONTINGENCY

VI. FUTURE WORK

Although there was some study of the effects of a single UPFC on the grid leading to the conclusion that load flow only needs to be computed for the effected part of the grid, it would be beneficial to study if this remains true for systems with multiple UPFCs. It may be possible to approximate the combined effects by superposition of the effects of individual UPFCs.

	Total Overloads	Overloads $> 10\%$	Overloads $> 20\%$
Maximum	30	26	20
Mean	0.6937	0.4707	0.3605
Std Dev	1.6135	1.3080	1.0758

TABLE III
SUMMARY OF MAX FLOW CONTROL FOR EACH POSSIBLE UPFC PLACEMENT AND EACH SINGLE LINE CONTINGENCY

The evidence presented indicates that the objective function being used here has only global minima, even when multiple UPFCs are being used. There are some questions that still need to be resolved before it is known whether SQP can be used in large systems:

1) Are local minima present, but ignored due to the quadratic approximation?
2) Does a quadratic model accurately approximate the objective function?
3) Are local minima prevalent in other systems?
4) Can it be proven that only global minima exist?

The answers to these questions may prove that SQP can be used in general to find global optima.

It is also important to compare SQP techniques to more common power system optimization techniques like Optimal Power Flow (OPF) [4]. Comparing both the computational complexity and quality of modeling may show the relative strengths and weaknesses of each technique.

Although the work presented here incorporated the effects of reactive power flow in the system, the UPFC's ability to control reactive power flow was neglected. The optimization process can be amended to include reactive power flow control, which should result in a further improvement in the system quality.

One of the biggest impediments of UPFC usage is the complexity of choosing optimal installation locations. As can be seen here, UPFCs can be used for both power flow compensation and for power flow restriction; they may be used on chronically congested lines in a restrictive manner or as means of increasing power flow through lightly loaded lines to draw power away from the congested area. This duality makes nearly every line in a power system a possible candidate for UPFC installation. In order to compare possible installation locations, the UPFC's control algorithm must already be known a

	Max Flow	SQP
Realism	Restricted to Real Power Flow only. Ignores reactive power and line losses.	Based on physical system power flow, implicitly includes reactive and losses.
Reliability	Guaranteed, but non-unique solution.	Depends on convergence of SQP and loadflow. May fail in extreme circumstances.
Speed	Simple and fast algorithm	Emperical evidence indicates suitable for online control
Resources	Global system knowledge	Global system knowledge

TABLE IV

COMPARISON OF MAX FLOW CONTROL AND SQP CONTROL

priori. In addition, the size of the UPFC itself is a critical parameter. In the work presented here, it was assumed that the UPFC would be large enough to change the line's power flow by up to ±20% of the line's capacity ($Smax_{ij}$), but this is both unlikely and unnecessary. The form of SQP presented here may be used to evaluate the quality of potential UPFC locations because it is capable of finding the optimal set points for multiple UPFC locations and it may be extended to determine the optimal size of UPFC to install by including an economic model indicating the costs of different control ranges. For instance, in one particular location a UPFC with only ±7% control may be sufficient and may cost only a fraction of a larger UPFC with ±20% control that may be necessary in another location. An economic model may be used to select several small capacity devices rather than a few large devices or a combination of devices of various sizes.

VII. CONCLUSIONS

Based on the empirical evidence, SQP is a good choice for finding the optimal set points for systems with several UPFCs. The form of SQP used here, which uses load flow directly, has the ability to incorporate both real and reactive power flow measures in whatever optimality criteria is chosen. The optimality measure used, which was designed to improve fault tolerance via better power distribution, appears to be smooth and have a single global optimum, even in systems with multiple UPFCs. If it can be proven that it is concave, then SQP is guaranteed to find optimal set points. Both the size and number of load flow computations, on which SQP optimization relies, seem to have reasonable bounds. Based on these findings, SQP appears to be a good candidate for real-time control of UPFC set points.

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BIOGRAPHIES

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