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William M. Siever

Radha P. Kalyani

Mariesa Crow
Missouri University of Science and Technology, crow@mst.edu

Daniel R. Tauritz
Missouri University of Science and Technology, tauritzd@mst.edu

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UPFC control employing Gradient Descent Search

W. Siever*, R. P. Kalyani*, M. L. Crow*†, D. R. Tauritz†‡

Abstract— **Increasing demand coupled with limitations on new construction indicate that existing power transmission must be better controlled in order to continue reliable operation. Recent advances in FACTS devices provide a mechanism to better control power flow on the transmission network. One particular device, the Unified Power Flow Controller (UPFC), holds the most promise for maintaining operation even when the system has suffered partial failure (either naturally occurring, due to human error, or a malicious attack). In addition to the capital cost, the primary obstacles to widespread UPFC use are the combined problems of selecting the most cost effective locations for installation and maintaining proper control of them once installed.**

In this paper we list evidence that Gradient Descent search based on load-flow computation is more realistic and accurate than many of the optimization techniques currently in use. We then demonstrate that Gradient Descent search can be used to select control points that improve system fault tolerance more than those found by the Max-Flow technique. In addition, we demonstrate that the size of the system being computed and the number of computations is bounded and is practical for real time control.

KEYWORDS. *FACTS, UPFC control, Gradient Descent search, Max-Flow control*

I. INTRODUCTION

Over the past few decades, demand for electric power has continued to increase while social, economic, and environmental factors have limited the expansion of the existing power transmission infrastructure. This phenomenon often leaves the existing infrastructure operating in a stressed state — where several components are operating near their rated capacity. In such cases, a few failures in the system can cause excessive burden on the remaining components and eventually lead to cascading failures similar to the 2003 blackout that affected a large portion of the north-eastern U.S. and parts of Canada.

Since it is unlikely that the factors limiting infrastructure expansion will be resolved in the near future, it is paramount that the current infrastructure be optimally utilized. One of the most promising technologies for improving the utilization of current power transmission facilities is a family of power transmission devices known as Flexible AC Transmission System (FACTS) devices. A variety of different FACTS devices have already been installed world wide and have been shown to be both economically advantageous as well an improvement to system reliability while minimizing new construction [1, 2].

One of the most powerful of these types of FACTS devices is the Unified Power Flow Controller (UPFC). The UPFC is of particular interest for improving the quality of transmission utilization due to its ability to actively control the real power transmission through an individual line. This in turn helps regulate the power flow through other lines in the system. The two major obstacles to widespread UPFC installation are selecting ideal installation locations and then implementing suitable control algorithms to ensure optimal performance.

In this paper, we examine improving fault tolerance by using UPFCs to control system power flow. In particular, we examine the feasibility of standard Gradient Descent search techniques as a means of achieving optimal control. The empirical evidence presented here indicates that Gradient Descent techniques may be suitable for updating a UPFC's control set point in real-time.

II. UPFC CONTROL

Multiple algorithms have already been proposed for improving fault tolerance via UPFC control [3, 4]. Here, we find that a simple line-search based form of Gradient Descent search [5] may be an acceptable form of on-line control. We chose a performance metric that reflects the number of lines that are close to, or exceed, their rating:

$$\sum_{\text{all lines}} \left(\frac{S_i}{S_i^{max}}\right)^{2n} \qquad (1)$$

where S_i is the apparent power flow through line i and S_i^{max} is the apparent power flow rating for line i. This equation is based on a similar overload performance index used for ranking contingency severity [6]. This particular metric has a higher "penalty" for lines that are more highly loaded. In fact, by varying n the amount of disparity between overloads and near-overloads can be dramatically

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*Electrical and Computer Engineering, University of Missouri-Rolla, Rolla, MO 65409

†Intelligent Systems Center, University of Missouri-Rolla, Rolla, MO 65409

‡Computer Science, University of Missouri-Rolla, Rolla, MO 65409

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increased. However, all work presented here assumes that $n = 1$.

Most proposed control techniques suffer some limitations when applied to security enhancing optimizations. The most common limitations are that they:

1. assume the system is linear,
2. neglect the effects of reactive power,
3. rely on complex partial derivatives, or
4. decouple active and reactive power flows which may affect convergence.

Many of the previously proposed techniques rely on additional constraints being incorporated into traditional optimal power flow techniques. The data presented here indicates that a Gradient Descent search coupled with standard load-flow tools may be a feasible alternative for on-line control without the previously mentioned disadvantages.

III. System Model

The power transmission network can be represented as a set of buses interconnected with lines of known series impedance with a maximum rated power capacity. 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 known values and the other two are unknown (which variables are known and which are unknown depends on the type of bus). The most common way to solve for the unknowns is the Newton-Raphson technique of computing load flow [7, 8, 9]. 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 controlling the specific amount of power flow through a specific line. By controlling the power flow through a specific line, the power flow across the remaining lines in the system will adjust according to the physics of the system. The UPFC is modeled as a mechanism which delivers real power to one bus and draws a corresponding amount of real power from another bus while maintaining the voltage magnitudes at both sending and receiving ends. The UPFC was idealized in that it was assumed to be lossless and was assumed to be able to explicitly control the line power flow up to the line's real power flow capacity.

All examples here are based on the IEEE 118 bus test system[1] with a highly stressed load and generation profile. Of the 186 lines in the test system, 167 are considered as potential candidates for UPFC installation and 177 are considered as subject to contingencies. Certain lines were eliminated from consideration due to their location and/or their outage would cause instaneous islanding of the system. The work presented evaluates only only single-line contingencies (SLCs), which are situations in which only a single line is outaged, and the installation of only a single UPFC. Neither cascaded outages nor load shedding were considered in this work.

IV. Feasibility of technique

In order to determine if Gradient Descent techniques are capable of being used in on-line control, it is important to establish that they have computational requirements can be satisfied in real time. In the Gradient Descent search process, load flow solutions are performed numerous times during the optimization process. Therefore the computational efficiency depends on both the number of load flows performed as well as the complexity of each load flow.

A. *Estimate of bounds on load flow complexity*

There are multiple variations on load flow which can be used to divide the system into regions, each of which can be treated as a smaller independent system. Generally, the load flow computation is proportional to the square of the size of the system, so it is vital that control algorithms which are dependent on load flows be able to utilize the smallest "area" possible. If we assume that most UPFC installations will only impact a fixed size portion of the transmission system, then only that region must be considered in the load flow solution.

One way of estimating the size of the area that a UPFC impacts is to calculate the degree to which the system changes when a UPFC is placed at a particular location and adjusted to its maximum and minimum settings. Table 1 shows a summary of the number of lines affected and the degree to which they are affected for all 186 possible UPFC locations. Note that although many lines experience a minor deviation, on average, only 28 lines experience more than a 5% deviation in power flow and no more than 89 experience more than a 10% deviation for any of the possible installation locations. Moreover, note that these are all extreme cases where the UPFC is set to its maximum limit. Overall this indicates that only a moderate part of any system needs to be used for a load flow based optimization.

Table 1. Line Affects for all possible UPFC placements

% Dev of S	Min Lines Affected	Max Lines Affected	Mean Affected	Std Dev
> 1%	9	149	53.83	27.53
> 5%	3	110	27.68	19.31
> 10%	1	89	18.96	15.57
> 15%	1	77	14.77	13.17
> 20%	1	70	12.16	11.40
> 25%	1	64	10.49	10.21

B. *Number of load flows performed*

The number of load flows that must be performed is also a vital consideration when considering Gradient Descent

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

Table 2. Summary of Line Effects for all possible UPFC placements

Starting Point	Load Flow Failures	Min # of Load Flows	Max # of Load Flows	Mean # of Load Flows	Std Dev
Random	304	4	36	8.35	1.62
Max-Flow	722	4	46	8.28	1.95

search for on-line control. Gradient Descent techniques require an initial starting point to begin the minimization. The choice of the initial point can have tremendous impact on the speed of convergence to a control point. To develop an empirical estimate of the bounds on the number of load flow calculations each possible UPFC location was tested against all possible single-line contingencies. In addition, both a random starting point and a recommended value produced by the Max-Flow algorithm were tested [3]. Table 2 shows a summary of the number of load flows performed for single test case of each technique over all placements and all contingencies (167 placements and 177 possible contingencies). In some cases the load flow procedure failed either due to excessive number of iterations or a singularity in the system.

The choice of starting point does make some difference in the rate of convergence. Note that when a Max-Flow initialization was used, the number of failures also increased, however these failures still represent a small portion of the total number of load flows run (29,559).

V. QUALITATIVE IMPROVEMENT

One of the interesting advantages of using Gradient Descent search with the proposed performance metric (Equation 1) is that it shows a qualitative improvement over Max-Flow based control. Figures 1(a) and 1(b) show the differences in the metric used and, more importantly, Figures 1(c) and 1(d) show the corresponding total number of overloaded lines for each technique. Each figure shows a section of the possible UPFC placements and possible contingency conditions. A comparison of the Gradient Descent search optimized values versus the Max-Flow values shows a clear improvement from the usage of Gradient Descent search with the proposed performance metric.

Over all possible combinations of UPFC placement and line outage, Max-Flow control results in a total of 150,108 line overloads while the Gradient Descent search optimized values only cause 41,335 line overloads.

VI. CONCLUSIONS

Gradient Descent search employing the line-search technique appears to be an improved method of identifying optimal UPFC set points compared to other current techniques. The number of load flows necessary to find an optimal control is small enough to be practical for on-line control. In addition, since the UPFC effects only a small portion of the power grid, the load flows only need to include the effected lines rather than the entire system. Finally, the metric optimized seems to provide substantially better system capacity than that realized by Max-Flow techniques.

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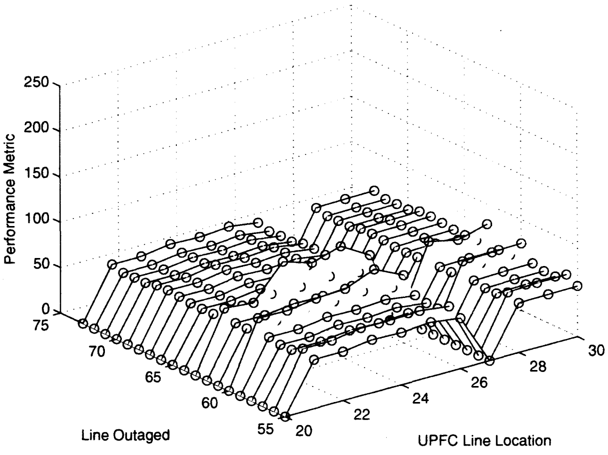
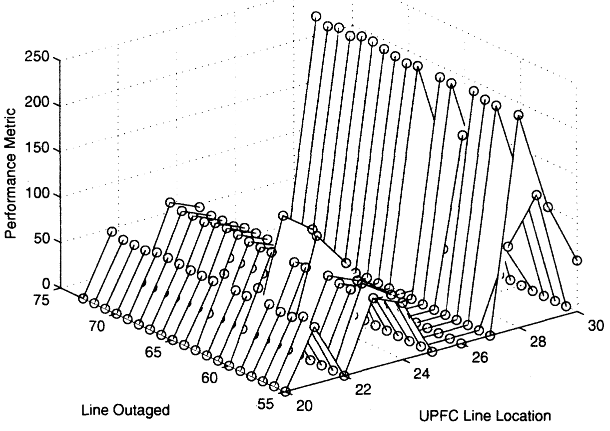
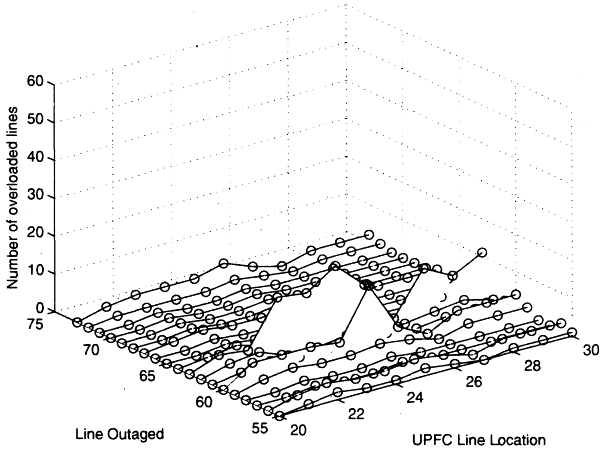


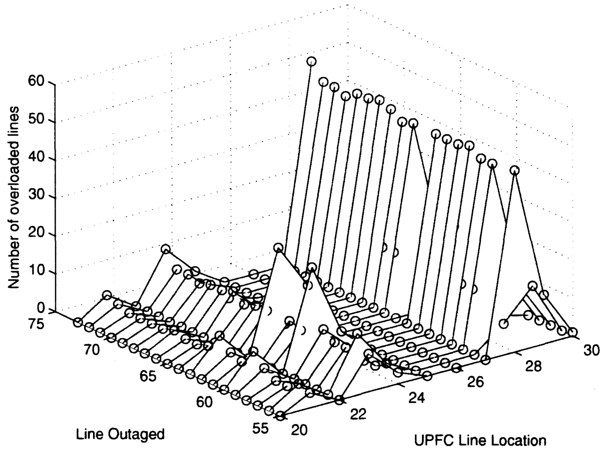
(a) Gradient Descent Minimum metric value



(b) Max-Flow Minimum metric value



(c) Gradient Descent's number of overloaded lines



(d) Max-Flow's number of overloaded lines