COST/BENEFITS ANALYSIS OF AN OPTIMAL POWER FLOW: THE PG&E EXPERIENCE

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ABSTRACT: This paper documents the results of a study to analyze the potential costs and benefits that may be realized from the future on-line use of an Optimal Power Flow (OPF) application in PG&E's new Energy Management System (EMS). This application minimizes production cost while eliminating thermal overloads using active power controls. The methodology of the study was to simulate as closely as possible the operation of the PG&E power system under the currently used method based on a modified economic dispatch algorithm and the optimal dispatch provided by the OPF. The modified economic dispatch method is based on an economic dispatch with some manual re dispatching to eliminate thermal overloads consistent with existing operating procedures. The results of the study showed that the use of this OPF application resulted in a substantial increase of the MW transfer capability of a constrained transmission corridor in the PG&E system. This increase can potentially result in substantial annual savings due to reduced operating costs. Furthermore, the study showed that this application can minimize load shedding, if the other control options have been exhausted, to eliminate thermal overloads, can produce realistic solutions for infeasible problems and could conceivably validate/improve current operating procedures under a wide range of operating conditions.

KEYWORDS: Cost, Benefits, Optimal Power Flow, OPF.

I. INTRODUCTION

The purpose of an Optimal Power Flow (OPF) function is to schedule the power system controls to optimize an objective function while satisfying a set of nonlinear equality and inequality constraints. The equality constraints are the conventional power flow equations; the inequality constraints are the limits on the control and operating variables of the system. Mathematically the OPF can be formulated as a constrained nonlinear optimization problem. Different classes of the OPF problem tailored towards special-purpose applications are defined by selecting different functions to be optimized using different sets of controls and different sets of constraints. All these classes of the OPF problem are subsets of the general problem. Historically different solution approaches have been developed to solve the different dasses of the OPF problem.

It would be difficult to accurately classify all the approaches that have appeared in the literature, since many employ a mix of specific methodologies. However, it seems that the most promising ones that have been developed over the last ten years are based on real and reactive power decoupling [1], successive sparse quadratic programming [2], successive nonsparse quadratic programming [3], successive nonsparse separable programming [4-7], Newton's method [8],[9] and Interior Point Method [10],[11]. Some of these techniques have resulted in production OPF programs that have obtained a fair level of maturity and have overcome some of their earlier limitations in terms of flexibility, reliability and performance requirements. However, many times they are plagued by weak convergence, unrealistic assumptions, poor input data and inadequate models of the power system to be able to solve real life problems. These limitations become especially apparent in an on-line environment where operational problems impose the most onerous requirements on the OPF technology. Although these deficiencies may potentially limit the practical value and scope of OPF applications they have not received adequate attention in the industry. The deficiencies exist because significant aspects of the OPF problem in an on-line environment have been overlooked or ignored. In most cases there is a good reason for that; realistic treatment of the problems leads to very complicated and intractable formulations that are not amenable to existing classical mathematical optimization techniques. Simplistic formulations and solutions that might be sufficient for other applications, e.g., planning studies, are usually unrealistic and produce unacceptable results.

PG&E as part of its efforts to improve system operations has invested many man-years in defining, developing and implementing an OPF function. Our EMS optimization capability presents one of the first serious attempts to move away from simplistic formulations for the on-line optimal scheduling problem and focus on implementations that meet specific operational requirements. Although it falls short of fulfilling all realistic requirements it is suitable for getting started with wide industrial on-line applications. Many such applications that meet specific operational needs have been identified and ranked according to their perceived value and implementation risk [12]. The first application that was chosen as a candidate for implementation in an on-line environment calls for the minimization of production cost while satisfying all thermal constraints using active power control only. This incremental approach to the introduction of the OPF in an on-line environment was deemed necessary given the level of analysis capabilities currently available and the sophistication of the OPF technology.

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The first application has completed an initial phase of field testing and plans are being developed to make it a useful and usable product. As a result of this testing, it was discovered that a host of practical implementation problems, not previously fully analyzed, needed to be overcome in establishing a fully operational OPF application. Some of these problems include:
initial start up, tuning, maintenance and performance requirements; case setup and interpretation of the OPF results; modeling of the external system suitable for optimization; effect of the OPF application on the EMS computers; user friendly MIMI and user training. The investment in money, time and manpower to successfully address these problems should not be overlooked. On-line OPF applications constitute a quantum leap of technology in existing control centers and the effort involved in tuning, maintenance, training, etc., is substantial, especially during the first few years of operations. OPF applications are not a requirement for dispatchers to perform their duties. A dispatcher does not necessarily need to use OPF applications to "get by." Therefore training dispatchers to use OPF applications takes on special requirements whereby one is not only interested in teaching the basics of these tools, but providing incentives and motivation for their usage. One such major incentive is clearly a cost/benefits analysis study that would quantify the added value of the application to system operations. We decided to undertake such a study as part of our efforts to make the first OPF application fully operational. It is our hope and expectation that the experience gained from the testing and use of the first *OPF* application will pave the way for the successful implementation of additional OPF applications.

The objective of the study was to identify and roughly estimate the potential costs and benefits realized from the future on-line use of the first OPF application. The objective was not to provide an accurate assessment of the benefits - probably an illusory goal given the uncertainties of the system operations and the lack of sufficient data - but to provide an indication of the potential added value of the application to system operators. Such an indication would provide an incentive to the system operators strong enough to warrant full use of the application in the on-line environment.

This paper reports on the results of this cost/benefits analysis study. Section II provides an overview of the methodology of the study. Section III describes the test cases and the set of contingency outages chosen to simulate actual operating conditions. Section IV presents the results of the simulations using the modified economic dispatch, that is currently in use, and the OPF dispatch methods. Section V summarizes the conclusions of the study.

II. COST/BENEFITS ANALYSIS METHODOLOGY

The basic methodology of the study was to simulate as closely as possible the actual system operations for a variety of operating conditions using the modified economic (ME) and OPF dispatch methods. The currently used ME dispatch method is based on an economic dispatch with some manual re-dispatching to eliminate thermal overloads consistent with current operating procedures. The solutions recommended by the OPF were scrutinized for compliance with established procedures. Both methods were used to produce a dispatch under the same operating conditions. An extensive. review of records of past system operations was undertaken to determine the set of operating conditions and the credible contingency outages that needed to be simulated. Detailed simulation of these conditions was deemed necessary to produce acceptable results. Other simpler approaches, that scale the results of previously published studies to a particular utility's characteristics, were considered but were not adopted because it was felt that the introduced uncertainties were too large to ignore [13-15]. Similar cost justification studies have been described in [16], [17].

The MW production differential between the OPF and ME dispatches was used to determine the benefits, or loss thereof, that would be realized from the future use of the OPF. Benefits were derived for specific conditions that are representative of the PG&E system operations. Actual translation of the benefits to annual dollar savings, however, was not performed to avoid unnecessary assumptions regarding the time applicability of the realized MW savings. As a result, the study stands to show how this OPF application could be used to better identify the operational boundaries of the system.

The study concentrated on identifying and more clearly defining the potential operational boundaries in two specific aspects of system operations related to the scope of the first OPF application. Certainly, there are other aspects that were not quantified due to various reasons. But it was felt that the resulting benefits would still provide a strong incentive for the application to be fully used in system operations. The study also identified some other benefits that were difficult to analyze due to lack of sufficient data. These benefits hereafter will be referred to as non-quantifiable benefits. In the remainder of this section a brief description of the analyzed aspects of system operations and the non-quantifiable benefits will be given.

The first analyzed aspect of system operations was associated with the elimination of thermal overloads. Under current operating guidelines, the system is dispatched so that thermal overloads do not occur. The time duration per year that the system is in a thermal overload condition is very small. According to the 500 kV transmission outage records for 1990, the total number of 500 kV forced network outages was 103 hours. The average duration of a 500 kV outage was typically about one hour. Correspondingly, the availability of the PG&E 500 kV network is very high (well over 99+%). The potential production cost savings from the future use of the OPF for an outage that resulted in a thermal overload was essentially the product of the difference between the OFF and ME dispatch solution costs and the time duration of the outage. As a result of the short duration of the outages and the corresponding thermal overloads, it is expected that the potential production cost savings from the future use of OPF dispatch would be rather small.

The second analyzed aspect of system operations was related to the preventive mode of the PG&E system operations in order to stay below emergency thermal limits on the transmission system due to the occurrence of single contingency outages. PG&E operates its system in the preventive mode in some areas for long time periods in order to eliminate emergency thermal overloads, or minimize the severity and duration of overloads caused by single contingency outages. An example of preventive operation is associated with the heavy South to North flows on the PG&E 500 kV network which may occur during the winter months. Given the long duration of operations in preventive mode, even small efficiency improvements could potentially result in large savings. Consequently, it was expected that substantial production cost savings associated with the preventive mode of operations could be captured from the use of the OFF application.

There are also several non-quantifiable benefits related to the use of the OFF in an on-line environment. One of the benefits results from the potential reduction in the amount of load shedding used as a control of last resort to eliminate thermal overloads. The benefit is of substantial value, even though this control is rarely used by PG&E, given the negative impact load shedding might have on public perceptions. Another benefit is the reduction in the over-stressing of the equipment which can shorten their operating life. This benefit was also not quantified but it is possible that OPF dispatch solutions could conceivably provide some relief in over-stressed equipment which may lengthen their operating life. Another benefit realized from the use of the EMS OPF is associated with the capability to develop optimal operating strategies for power system problems using real-time data. Presently, power system engineers develop operating guidelines to address various problems based upon numerous studies performed in an off-line mode. These operating guidelines are very broad in scope to handle a wide range of operating conditions. Consequently, to ensure safe and reliable operation of the power system, the operating instructions are necessarily conservative. As a result, the power system may not be operated as efficiently and/or as economically as possible given the actual operating conditions. The EMS OPF could conceivably be used by power system engineers to develop optimal operating guidelines to maximize efficiency and economy. It could also be used by system operators to determine optimal control settings to handle real-time operating problems.

Another important benefit that was not analyzed is related to the on-line OPF capability to formulate corrective/preventive remedial plans for unforeseen events that may not be covered under existing operating guidelines. Even though numerous hypothetical operating conditions are usually analyzed it is conceivable that certain unusual, nevertheless possible, conditions may have never been studied. This is usually the case when the system is in a second order contingency condition for which operating guidelines may not be readily available. Also when the envelope of system operations is extended to unfamiliar conditions for which experience and historical records may be of little use, existing guidelines will probably not suffice. This will certainly be the case as utilities move toward a more open and competitive environment and increased third party generation, such as qualifying facilities and cogeneration, will seek access to their markets. Evaluation of requests for transmission access in the context of the system security will put a high premium on utilities to respond rapidly to an increasing number of energy suppliers. These suppliers will undoubtedly stress the system even further and will push it into operating modes for which guidelines may not be available. The first OPF application could conceivably produce rapid remedial plans for these unusual operating conditions.

III. TEST DATA DESCRIPTION

The network base cases selected for this study were based on the 1990 summer peak and winter off-peak cases because they were the most recently completed cases which exhibited thermal overloads due to heavy loading. Also, a number of actual contingency cases were extensively reviewed and selected for the simulation studies. These contingency cases consisted of outages that caused thermal overloads. The selected contingency cases represented outages of the following power system equipment. a) Table Mountain-Tesla 500 kV line outage, b) Tesla 500/230 kV bank outage, c) Metcalf 230/115 kV bank outage and d) Los Banos-Midway 500 kV #1 line outage. The first three contingencies were simulated using the summer peak base case, while the fourth contingency was simulated using the winter off-peak base case.

The Table Mountain-Tesla 500 kV line outage was examined to study the effects of a 500 kV line outage with a heavy North to South 500 kV Intertie flow. The Tesla bank outage case required extensive corrective redispatch. There are two 500/230 kV transformer banks at the Tesla substation. With one bank out of service during high peak load conditions, the second bank would overload to approximately 122% without any corrective control action. The Metcalf bank outage required startup of Gas Turbines, network switching and load shedding as corrective actions. With one 230/115 kV bank out of service at the Metcalf station, the other 230/115 kV bank would overload to approximately 150% without any corrective action. Finally, the outage of the Los Banos-Midway 500 kV #1 line (actually the Los Banos-Gates section) at an off-peak winter system load of 7900 MW with a heavy South to North Intertie flow was also studied. It was assumed that inexpensive Southwest energy was available at 12 $/MWh. This assumption may not be always true. Although Southwest energy may be available at the source at a reasonable price, transmission constraints outside of California. depending on operating conditions, may prevent access to this energy. Preventive action was necessary to prevent overloading several 230 kV lines and a 500 kV series capacitor bank during the outage. One of the main characteristics of this outage case was the limitation of the South to North power transfer, which occurs primarily during the winter and occasionally during the late autumn and early spring months.

Hydro conditions were assumed to be similar to the drought conditions of the past several years. The gamma values (worth of water) of the hydro units used in both dispatch methods were calculated using the PG&E's Hydro-Thermal Optimization (HTO) program based on the load levels, thermal generation levels and hydro conditions of the simulated base cases. These hydro unit gamma values were held fixed for all test cases. In actuality, the hydro unit gamma values should be re-calculated on-line to reflect actual operating conditions. Unit incremental cost curves, 1991 fuel costs estimates for the thermal units and equivalent fuel costs for the hydro units were obtained from the EMS database.

IV. STUDY RESULTS

The simulation results for the base cases and the contingencies produced by the currently used ME method and the proposed OPF dispatch method are summarized in this section. For the cases in which the ME dispatch solution includes overloads coming from the base case, two OPF dispatch runs were made. The first OPF dispatch solution was produced by minimizing the production cost and eliminating all thermal overloads in the power system. This solution is referred to as constrained OPF dispatch. The second OPF dispatch solution was provided by minimizing the production cost and eliminating all constraints except those that were allowed in the ME dispatch solution. This solution is referred to as relaxed OPF dispatch. The creation of relaxed optimal dispatch solutions was necessary in order to replicate the same conditions for a valid comparison of production cost between the ME and OPF dispatch solutions. Obviously the violations in the ME dispatch cases could have been eliminated by expanding the control set to include additional control facilities such as Gas Turbine generators (GTs). However such an action was not simulated because it was felt that the production cost differentials would not significantly change and the simulation results of the economic analysis would be approximately the same. Controllable generation consisted of hydro and conventional steam/fossil units on AGC. The production cost was calculated using the controllable generation only. Non-controllable generation consisted of base loaded generation, including the Diablo Canyon nuclear plant, embedded utility generation and generation from Qualifying Facilities.

The simulation results for the summer peak base case and the associated three contingencies are as shown in Table 1. The simulation results fur winter off-peak case and the Los Banos - Midway line outage are shown in Table 2. The total system production cost for the summer peak base case using the ME dispatch method was estimated to be $175,368.94 per hour. The production cost for the constrained OPF dispatch solution was $175,372.77 per hour which amounts to an increase of $3.83 per hour with respect to the corresponding ME solution. This economic penalty resulted from the constraints violation enforcement. The production cost for the relaxed OPF dispatch was $175,146.36 per hour which amounts to cost savings of $222.58 per hour with respect to the ME solution. It is expected that the potential cost savings at lower load levels could be significantly larger due to the greater maneuvering margin available to the OPF controls.

The ME dispatch solution for the Table Mountain-Tesla 500 kV line post-outage case using the summer peak base case resulted in several overloads. In actual operations, this solution would be further adjusted to eliminate the overloads. The production cost was $182,699.34 per hour. As noted earlier, two OPF dispatch solutions were produced for this post-outage case see Table 1). The constrained OPF dispatch eliminated the thermal overloads at a production cost of $l82,763.47 per hour, a cost increase of $64. 13 per hour with respect to the ME dispatch

Table 1: Production Cost for Modified Economic and OPF Dispatch Solutions ($/Hour)
Summer Peak Base Case

Simulation Case	Modified Economic Dispatch	Constrained OPF Dispatch	Relaxed OPF Dispatch
Summer Peak Base Case	175,368.94	173,372.77	175,146.36
Table Mt Tesla 500 kV Line Outage	182,699.34	182,763.47	182,174.70
Tesla 500/230 kV Bank Outage	176,447.70	(1)	176,271.20
Metcalf 230/ 115 kV Bank Outage	190,500.50 (2)	191,522.44 (2)	187,019.20 (2)
	188,779.35 (3)	201,385.34 (3)	(3, 4)

Table 2: Production Cost for Modified Economic and OPF Dispatch ($/Hour)
Winter Off-peak Base Case

Simulation Case	Modified Economic Dispatch	Constrained OPF Dispatch	Relaxed OPF Dispatch
Winter off-peak Base Case	42,743.06	42,100.81	(4)
Los Banos-Midway 500kV Line outage	44,004.32	43,486.18	(4)

Footnotes:

(1) For this test case, the constrained OPF dispatch was infeasible.
(2) In these test cases, load shedding was manually implemented (i.e., load shedding was not available as a control option).
(3) In these test cases, load shedding was included in the control set.
(4) In these test cases, there was no need to perform a relaxed OPF dispatch solution.

solution. The relaxed OPF dispatch solution, that allowed the same level of overloads with respect to the ME solution to exist, reduced the production cost to $182,174.70 per hour. This amounts to cost saving of $524.64 per hour with respect to the ME dispatch solution for the same conditions.

The Tesla 500/230 kV bank outage was simulated using again the summer peak base case. The ME dispatch solution using existing operating guidelines that involved generation redispatch and switching operations eliminated the thermal overload on a parallel transformer bank. The production cost for this solution was $176,447.70 per hour as shown in Table 1. The constrained OPF dispatch failed to produce a feasible solution with all constraints enforced using only conventional generation sources as controls. Consequently, only the results of the OPF dispatch with relaxed constraints were provided in Table 1. The production cost for this dispatch was $176,271.20 per hour which amounts to cost saving of $176.50 per hour with respect to the ME dispatch solution. This test and many other similar tests performed during the implementation of the first OPF application strongly indicate the importance of branch switching and bus reconfiguration as a means available to the operator to enforce security constraints and eliminate overloads. Incorporation of these control options in an on-line OPF function would greatly expand its scope and enhance its credibility in a real-time environment.

The simulation for the 2 30/1 15 Metcalf bank outage requires some explanation. Elimination of the resulting violations for this outage required the use of load shedding. To evaluate the performance of the OPF in exercising this control option two cases were created that differed in the modeling of load shedding. In the first case the ME dispatch employed existing operating guidelines that involved load transfer to another station, load shedding of 183 MW and expansion of the control set to include Gas Turbine generators. The production cost of this dispatch was $190,500.50 per hour. (Note that this ME dispatch solution still included some minor violations originated from the base case and no attempt was made to eliminate them.) The constrained and relaxed OPF dispatch solutions corresponding to this ME solution with production costs of $191,522.44 per hour and $187,019.20 per hour respectively, employed the same manual adjustments to achieve feasibility. In both optimized cases no load shedding was used as a control option. In the second test case no manual load shedding was performed and it was left up to the OPF to determine the level and location of load shedding required to achieve feasibility. In this case the constrained OPF dispatch reduced the amount of load shedding by 30 MW to 153 MW at a cost penalty of $10,884.84 per hour over the corresponding ME dispatch solution. In this case the ME dispatch solution had no violations, so there was no need to produce a relaxed OPF dispatch solution.

The Los Banos-Midway 500 kV #1 line outage (Los Banos-Gates section) was applied to a winter off-peak base case of 7900 MW. The ME dispatch solution for the base case had a production cost of $42,743.06 per hour and no overloads. Based on standard operating guideline for the given conditions, the South tie flow was restricted to 1319 MW. The constrained OPF dispatch had a production cost of $42,100.81 per hour and no overloads. This amounts to a cost savings of $642.25 per hour. Since the ME dispatch solution had no overloads, there was no need to produce a relaxed OPF dispatch. Furthermore the OPF dispatch was able to increase the South tie flow by 75 MW to 1394 MW and yet it was able to meet the post-outage line/transformer constraints with the OPF post-outage corrective control actions. The increase of MW transfer capability by 75 MW in this part of the system, coupled with cost savings or $642.25 per hour, is a result of major importance, since it clearly illustrates that, with the use of the OPF, PG&E can better define operational boundaries and as a result more fully utilize system resources. Better utilization of system resources will result in substantial annual savings due to reduced operating costs. The actual annual savings will depend on the percentage of the time in a year that an increase in the MW transfer capability of such magnitude can be sustained. However, with even modest time duration, the annual benefits are still substantial to warrant the use of the application in an on-line environment provided that implementation hurdles can be overcome. This is especially true if additional benefits from preventive operation in other parts of the system materialize. For the outage conditions the ME and constrained OPF dispatch production costs were $44,004.32 per hour and $43,486. 18 per hour respectively.

As can be seen, the primary potential benefits from the use of the first OPF application were obtained using the preventive operating mode, as exemplified by the winter off-peak base case simulation results. There were additional benefits due to the elimination of the thermal overloads in the corrective operating mode, but these benefits were negligible in size compared to the benefits realized from improving the preventive operations. The estimation of the cumulative savings for the life of the application will depend, among other factors, on the time applicability of the increase of the MW transfer capability, the changing operating environment and the annual fuel price increases. Furthermore, one should also keep in mind that this application covers a very limited scope of the capabilities provided by a generic OPF function. Consequently, the reported results represent only a small fraction of the benefits that may materialize from the use of a program that covers the full spectrum of OPF capabilities. The annual and total life span costs are expected to be used to enhance and maintain the first OPF application. A realistic cost estimate should be based on a three man-months of OPF maintenance effort per year and taking into account salary increases.

V. CONCLUSIONS

In this paper, we described a study for analyzing the potential costs and benefits that may be realized from the future on-line use of an OPF application in PG&E's new Energy Management System (EMS). This application minimizes production cost while eliminating thermal overloads using active power control only. The methodology of the study was to simulate as closely as possible the operation of the PG&E power system under the currently used economic dispatch practices and the optimal dispatch provided by the OPF. The objective of the study was to identify the benefits realized from future on-line use of the application by better determining the operational boundaries of the system operations.

The study showed that under the assumptions used in this paper, the future use of the first OPF application can potentially result in an increase of MW transfer capability of a constrained transmission corridor by 75 MW. This increase of transfer capability coupled with inexpensive energy markets in Southwest is a result of major importance, since it clearly illustrates that PG&E can use an OPF to better define operational boundaries and as a result more fully utilize system resources. Better utilization of system resources will result in substantial annual savings due to reduced operating costs. The actual savings will depend on the percentage of the time in a year that an increase in the transfer capability of such magnitude can be sustained and the availability of inexpensive Southwest energy that itself is constrained outside of PG&E's service territory. However with even modest duration assumptions, the annual benefits are still substantial to warrant the use of the application in an on-line environment. During the study the following conclusions were also reached:

- Most of the potential cost savings are realized from improvements in the preventive operation of the system.
- The gamma values for hydro units can change significantly during a week and even during a day from hour to hour. Given their importance in producing a realistic optimal generation dispatch, it is recommended to always update them during OPF studies to reflect actual operating conditions.
- Load shedding is an important control option of last resort that should be used with care to produce realistic results for heavily stressed problems.
- Rapid feasibility detection and handling is extremely important for the OPF to gain acceptability in the on-line environment. The need to produce realistic solutions for infeasible problems will increase as proliferation of security constraints will tend to shrink the feasible region even further.
- An important way for the OPF to gain credibility in on-line environment is to validate existing operating procedures under a wide range of operating conditions.

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BIOGRAPHIES

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Ken Kato received his B.S. degree in Engineering from the University of California at Los Angeles (UCLA), M.S. and Ph.D. degrees in Electrical Engineering at the University of Southern California. He worked at Hughes Aircraft Company, Northrop Aircraft Company, and TRW Systems Group on aerospace projects involving Kalman filtering and optimal control theory. He worked at Southern California Edison on advanced application software for their Energy Management System. He was the manager of EMS advanced application software development at Rockwell International. Dr. Kato is currently a Lead Consultant at ECC, Inc. specializing in EMS advanced application functions. He is a registered professional engineer in the state of California.

Discussion

GUORUI ZHANG (ABB NETCOM Ltd. Tugi, Switzerland) The authors are to be congratulated for presenting an interesting paper on the cost/benefit analysis of an optimal power flow. The main advantages of using an OPF function are its capabilities of enforcing various types of power system security constraints and eliminating the existing constarint limit violations in the active power or/and reactive power optimization. Although the OPF function has been implemented in many Energy Management systems (EMS). However, the experiences of utilization of the OPF in an on-line environment are still very limited. Therefore the cost/benefits analysis of an OPF as presented in this paper from the utility's point of view is particularly welcome. The discussor is looking forward to further reports from the authors and other OPF users on the on–line implementation of the OPF. The following points, which are related to the OPF algorithms and on-line implementation of the OPF function, are raised for clarification.

- Branch Switching and Bus Reconfiguration The discussor fully agrees with the authors on that the incorporation of these functionalities would greatly expand its scope and enhance its credibility of the on-line implementation of the OPF function. The OPF function is based on a branch-node oriented network model without explicitly modeling the circuit breakers and isolators. There are also huge number of possibilities to do the bus reconfigulation in a large power system. Therefore it would be very difficult to fully incorporate these features in the OPF in an on-line environment. However, the predefined branch switching and bus reconfigulation according to the utility's operation guidelines can be manually specified when an OPF case is set up. A knowledge based expert system is required for helping the OPF user to specify the appropriate branch switching and bus reconfigulation when an OPF case is set up for some very severe contingency cases. Could the authors kindly comment on this ? Do the authors have any plan to incorporate these features in the OPF function in the near future ?

- Infeasibility Identification and Constraint Limit Relaxation The fast infeasibility identification and constraint limit relaxation are very important feature in the on-line OPF implementation. There are several schemes to perform the constraint limit relaxation depending on the OPF solution methods. One of the scheme is that when an infeasibility is identified, the network constarint limits causing the infeasibility are relaxed by predefined percentages and the OPF solution is continued without the need of the reinitialization of the OPF. The bottleneck of the system operation can thus be easily detected using this scheme. Another scheme of performing the constraint relaxation is to relax all the constraint limits by specified percentages and the OPF is reinitialized. The first scheme, if applicable, is more efficient than the second scheme. If the constraint limit relaxation is not acceptable. additional controls of lower priorities including load shedding will have to be considered. What kind of constraint limit relaxation scheme has been incorporated in the OPF used by the authors ?

- Spinning Reserve Consideration in the OPF From the security point of view, each utility is required to provide a specified level of spinning reserve and this spinning reserve should be allocated to a number of regulating generating units. Can the authors' OPF consider the spinning reserve requirements for each regulating generator unit ? Have the tests presented in the paper consider the generating units' spinning reserve requirement ?

- Implementation of the OPF Recommended Controls In an on-line environment, the most important point of the OPF implementation is how to perform the *OPF* recommended controls. Some of the controls may have to be done manually. All the controls should be coordinated such that all system security constraints are satisfied while the system is smoothly moved from the initial operating point to the optimal operating point. For a large power system, this will be a very difficult task if active and reactive power controls are considered in the OPF. It would be appreciated if the authors could kindly present some operation guidelines from the utility viewpoint on how to implement the OPF recommended control actions.

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A.D. Papalexopoulos, S. Hao, E. Liu, Z. Alaywan, and K. Kato: We thank Dr. Guorui Zhang for his interest in our paper and his valuable discussion. His insightful questions and thoughtful comments complement the paper and raise several interesting points regarding OPF algorithms. In the following, we would like to address his questions.

(1) branch switching and bus reconfiguration:

Branch switching and bus reconfiguration in an OPF program are equivalent to a large discrete action. In [A], an efficient discrete algorithm has been developed to handle discrete shunt capacitor/reactor controls. As mentioned in [A], the algorithm may be extended to include switching actions. However, the benefits of that extension are not clear at this point. Based on our experience, switching actions are not used very often in the transmission network. PG&E operators consider switching a very "costly" control action because of the risk of voltage instability and other reasons. Only certain combinations are allowed to be implemented in the field. Usually branch switching is used as a constraint enforcement tool. In any case, switching actions drastically change the topology and security of the network and introduce large non-linearities in the model that cannot be handled easily with smooth analytical OPF formulations. At the present time, we view switching outside the scope of the OPF problem. However, there is no inherent limitation in including switching actions in OPF formulations. For acceptable results, modeling of switching actions should be consistent with utility operating practices. A simplified discrete approach which performs necessary switching (before or in between iterations) in a continuous based OPF will probably be sufficient in most of the cases. We agree that a knowledge based expert system may be used to help operators to specify the appropriate branch switching and bus reconfiguration when an OPF case is set up for some very severe contingency cases. In this case, emphasis should be placed on including in the rule base as many pre-determined situations as possible to cover a wide variety of power system states.

(2) infeasibility identification and constraint limit relaxation:

In the PG&E OPF, an LP algorithm is used to solve the active power portion of the optimization problem. In this algorithm, the constraint limit relaxation is performed based on a least squares approach, if feasibility has not been achieved. In this case, quadratic cost curves are introduced to all constraints and limit violations become slack variables in the LP algorithm. With this implementation, only the bottleneck constraints will be relaxed in a least squares sense. This type of modeling, even though typical in the industry, many times leads to inaccurate results. Certain individual constraints may have exceptional properties and should be costed by exception to address their unique infeasibility characteristics. Utilities need to identify these constraints and modify the algorithm appropriately for acceptable results. The loss minimization portion of the PG&E OPF is solved by Newton's method. With this method if the OPF does not converge in the first set of iterations specified by the user, the constraint weighting factors, corresponding to the penalty functions associated with the load bus voltage limits and the branch flow limits, will be reduced successively until a solution is reached. This approach normally results in all constraints being met except for those load bus voltage limits and branch limits that are preventing feasibility. Special care should be taken in selecting the proper weighting factors to avoid numerical problems and produce acceptable solutions. Field experience with this feasibility approach indicates that in many instances the recommended optimal, but infeasible, solutions are not realistic and consistent with operating practices.

Based on PG&E's operational practices, two limits are used for transmission lines; normal and emergency limits. If the system is "normal," then normal limits should be enforced. If the system is heavily loaded and it is infeasible to enforce the normal limits, then the limits will be relaxed to emergency limits. However, the emergency limits will never be violated. Hence, in the OPF, we introduce a moderate quadratic cost (but still higher than typical generation costs) for the violation between normal and emergency limits as well as an extremely high cost for violations outside the emergency limits. With this implementation, the limit relaxation between normal and emergency limits is based on least squares, while relaxation outside the emergency limits is prohibited.

(3) spinning reserve consideration in the OPF:

MW reserve constraints were fully respected in the optimization process. However, in the current OPF version, MVAR reserve constraints are not modeled. Further development in this direction is encouraged given the increased importance of voltage/VAR control for the operation of many power systems.

(4) Implementation of the OPF Recommended Controls:

In the current version of PG&E's EMS OPF, we are able to specify the total number of control actions in an OPF solution. This will make the OPF solution more practical and suitable for an EMS real-time environment. In terms of implementation of the OPF recommended controls, in our opinion, there are two major issues: For the generation MW control variables in an active power optimization, the amp consideration may be very critical. There should be a to implement such constraints into the OPF solution. We are currently investigating some techniques that will incorporate ramp constraints into the OPF. On the other hand, for the voltage control variables in a reactive power optimization, the sequence of control actions will be critical. It is not straightforward to formulate this problem into the OPF solution algorithm. We suggest implementing some rule-based logic as a post processing to the OPF solutions. In general. limited experience is currently available regarding the implementation of a "trajectory" of the OPF control shifts that does not exacerbate existing violations or cause additional ones. The sequence in which the different control settings a altered may inadvertently create new problems. In general the trajectory is probably less important for thermal violation than for voltage problems.

The limited amount of time to correct constraint violations is in itself a security concern but it is further complicated by the fact that controls cannot move instantaneously. For some controls, the time required for movement is not trivial. This is an important consideration to be taken into account in designing a trajectory for the OPF solutions. For example, generator ramp rate can significantly restrict the speed with which active power is rerouted in the network. Delay times for switching capacitors and reactors, and transformer tap changing mechanisms can preclude the immediate correction of serious voltage violations. The time-urgency of the violations and the time-constraints on control movement can together determine the character of an OPF solution. If the violation is severe enough, slow controls that would otherwise be preferred may be rejected in favor of fast, less preferred controls.

Comprehensive guidelines and procedures need to be developed to resolve the trajectory problem in a satisfactory way. Utilities are encouraged not to overlook the significance of this problem in their efforts to develop on-line OPF applications.

[A] W.-H.E. Liu, A.D. Papalexopoulos, and W.F. Tinney, "Discrete Shunt Controls in a Newton Optimal Power Flow," IEEE Transactions on Power Systems, Vol. 7, November 1992, pp. 1509-1516.