

Challenges to Optimal Power Flow

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Abstract: This paper is based on material presented at the IEEE 1995 Winter Power Meeting Panel Session on *Challenges to OPF*, sponsored by the IEEE Working Group on Operating Economics. The paper contains a brief summary of the session followed by summaries.

INTRODUCTION

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The increasing demand for an OPF tool for assessing state and recommended control actions for off-line and on-line studies has been on the increase since the first OPF paper was presented in the 60's. The lack of uniformity in usage and definition has also been a source of challenge to developers/users in OPF. The increasing need for OPF to solve problems of today's deregulated industry, and the unsolved problems in the vertically integrated industry has caused the working group on operating economics, through task force, challenges to OPF to evaluate the capabilities of existing OPF, in terms of their abilities. OPF has enjoyed the renewed interest in a variety of formulations, through the use of advanced optimized techniques such as, Genetic Algorithms, Interior Point methods, simulated annealing method, decomposition and Newton's method, and their contributions have been significant. Several production grade software suites with a family of applications have been in the market place and various industry and research archives. In spite of all the investment and work to date on OPF, several questions regarding what challenges are before OPF remain to be answered.

1. From a planner/operational perspective? Is OPF able to provide self diagnostic checks, guide a novice to use and give easy to understand answers and minimize the intimidation of the highly theoretical framework of non linearity, complexity, unfeasibility and optimality that are important to an optimization theorist?
2. What challenges exist to OPF in a more competitive environment? The deregulated electricity market will seek answers from OPF to address a variety of different types of market participants, data model requirements and real time processing and selection of appropriate costing for each unbundled service evaluation.
3. As a special purpose application in EMS environment? To cope with response time requirements, modeling of externalities (loop flow, environment and simultaneous transfers), practicality and sensitivity for on line use.
4. As a real time control application? How well the future OPF provide local or global control measures to support the impact of critical contingencies, which threaten system voltage and angle stability simulated. Future OPF has to address the gamut of operation and planning environment in providing new generation facilities, unbundled transmission services and other resource allocations. Finally, it has to be simple to use and portable and fast enough.

Summaries of the presentations at the panel are presented herein to provide a working reference to needs and interest in OPF technology.

AN OPF USER'S PERSPECTIVE

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The future of OPFs is as bright as ever. Engineers continue to find new uses for those programs. However, they are still only used by a minority. Thus, the challenge to OPFs is to become as popular and as easy to use as conventional power flows.

This note examines what power engineers are using off-line OPFs for, what shortcomings they are encountering, and what solutions there could be to these problems.

OPF Uses

In general, OPFs are applicable when a) studying a problem that requires interactive use of conventional power flows, and

96 WM 312-9 PWRS A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the 1996 IEEE/PES Winter Meeting, January 21-25, 1996, Baltimore, MD. Manuscript submitted August 1, 1995; made available for printing December 21, 1995.

b) for cases involving conflicting and independent variables and requirements. Typical examples of OPF applications are:

- Base-Case Development. This is perhaps the most common OPF application. Well-conditioned cases are rapidly attained. Dozens of base-cases can be efficiently developed, following the same set of design rules.
- Voltage Instability, Maximum transfers (V-P Curve Approach) or minimum compensation requirements(Q-V Curve Approach) to attain voltage stability are obtained in a single solution. Other constraints such as voltage and/or thermal limitations, can be added.
- Flexible AC Transmission Systems (FACTS). OPFs will likely be used to “dispatch” the transmission network (e.g., series and shunt compensation) to overcome post-disturbance thermal and/or voltage violations.
- Economic dispatch, subject to: thermal constraints, voltage constraints, interface constraints (e.g., stability) and spinning reserve constraints. From this dispatch, marginal costs and transmission bottlenecks are easily identified.

Shortcomings

Typical problems OPF users run into are:

- Non-convergence due to infeasibility is common in OPF investigations. This can be the result of both “large” (e.g. voltage instability), or “small” (e.g. a few infeasible voltages) problems. Solutions are: a) clear diagnostics indicating those binding constraints making the solution infeasible, b) soft limits to allow for but minimize criteria violations, and c) use of judgment making sure that the necessary controls are presented to the program.

Learning Curve. There is a steep learning curve before results are obtained. Constraints must be carefully reviewed. Objective function costs must be “tuned”. Early OPF solutions must be examined to make sure that they are reasonable. This can be alleviated by: a) better diagnostics of the solution’s quality and b) restrict use of OPFs to situations where this learning curve investment will have a pay back.

Other problems involve the nature of OPF solutions:

- Conventional vs. OPF treatment of locally-controlling generator constraints. The conventional treatment of generator constraints is difficult to model in OPF programs. This problem is critical when considering non-optimization or post-disturbance generator performance. Depending on the application, solutions to the problem are: a) for voltage critical analysis, upper constraints on generator voltages, or b) “clamp” and/or penalty function logic.
- Other problems; discrete vs. continuous control, local minima, and problems with equivalents.

Finally, users are sometimes discouraged by the fact that an OPF looks and feels very much like a conventional power flow, but is actually very different. Novice users may find it difficult to grasp concepts such as: a) local (conventional power flow) vs. global (OPF) control b) the “cost” concept, and c) the need to provide sufficient controls to attain feasibility. Algorithms and methods should be as transparent as possible to the user.

Conclusions

OPFs have found valid application, are maturing, and are gaining acceptance. More work needs to be done, however, both in making the programs more “user-friendly”, and in explaining to potential users, the “OPF way” to look at problems.

CHALLENGES TO OPF FROM A PLANNING PERSPECTIVE

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As the power industry moves into a more competitive environment, use of the Optimal Power Flow will become increasingly more important in maximizing the capability of the existing transmission system asset. The Bonneville Power Administration (BPA) has used two different Optimal Power Flow programs; Power Technologies, Inc.’s PSS/OPF and a program written by CEPTEL (Brazil) under contract with BPA. Both of these programs have considerably different features and have been used for a variety of planning studies.

The current version of the CEPTEL program is primarily a shunt VAR planning program. It is capable of being used in a “corrective” or “preventive” mode. Another very desirable feature of the program is its ability to optimize shunt capacitors for more than one outage at a time. This was one of the primary reasons why CEPTEL was selected to write an OPF for BPA. Other desirable features of the program include allowing for both fixed and variable costs at a given shunt capacitor site as well as having a “zone of interest” feature which only optimizes reactive control facilities in a specific area.

The PTI program that BPA initially purchased (version 2.1) has several desirable features not available in the CEPTEL program. This program can be used for a different purpose. BPA purchased this program primarily for its ability to optimize series and shunt capacitors. In addition, this program recognizes line limits and has the ability to have flow constraints. However, the program used by BPA did not optimize for more than one contingency at a time nor the ability to operate in either a “corrective” or “preventive” mode.

BPA used OPF for planning studies including:

1. Shunt VAR Planning (including replacement of PCB Capacitors)
2. Series Capacitor Planning

3. Transfer Capability Studies (including those limited by voltage stability)
4. Reactive Interchange Studies
5. Loss Optimization Studies

The planning engineer requires that all lines and voltages are within limits while minimizing investment (including losses during normal operating conditions) in a particular area or zone of interest. During outage conditions, line loading and voltages are again desired within limits while minimizing investment (losses are generally unimportant during outages). It is important to obtain feasible solutions with a minimal amount of engineering time.

BPA's experience with these programs has been met with mixed results. From a planning engineer's perspective, these programs require significant skill to produce useful solutions. Therefore, it is recommended that these programs be used by experienced planning engineers who has a good background. Results need to be constantly questioned. The engineer must also keep in mind that the operations side of the utility may not be capable of operating the power system as optimally as solutions suggested by OPF. For this reason, it is very important to restrict the degrees of freedom the OPF program has to insure results are meaningful and operable. These programs also seem prone to "infeasible" solutions which have been very frustrating. Reasons aren't always obvious and more informative. error and infeasible messages are badly needed. It is better to obtain a solution rather than no solution at all. Hard constraints and time consuming iterations on unimportant parts of the network may be part of the cause for these infeasibilities.

On the positive side, the programs have been able to solve some very complex problems while minimizing investment. In addition, they have saved considerable engineering time and lead to innovative solutions as well as more efficiently utilizing the existing transmission system. For example, on one transfer capability study on a highly stressed, voltage stability limited portion of the BPA 500-kV grid, the OPF program developed a series compensation alternative that performed almost as well as the traditional line constructive alternative. On a PCB capacitor replacement study, the OPF program developed an optimal solution in a few runs for seven different shunt capacitor sites and over twelve different critical outages. Results of the OPF run were tested in the BPA power flow program for all contingencies and were found to be within limits. This saved considerable engineering time and capacitor investment. On another study, the OPF program was capable of zeroing the VAR interchange between BPA and the other major Northwest utilities by adding shunt capacitors. This information was very useful in identifying those utilities relying on BPA for reactive support and the

magnitude of the problem. This work was accomplished by just a few OPF runs and saved a substantial amount of engineering time over the traditional "trial and error" approach to solving this kind of problem.

There are several desirable features when looking for an Optimal Power Flow program from a planning standpoint. Programs that are very flexible and versatile are the most useful. A few of the more desirable features to look for are:

- Be capable of optimizing in a "preventive" or "corrective" mode.
- Be capable of optimizing for a set of contingencies.
- Have user assignment on the value of existing shunts, losses and generator vars.
- Be capable of clamping generators, reactive and reactive control devices in unoptimized areas to base case settings.
- Be capable of holding VAR output of any generator.
- Be able to maintain reactive reserve at generators.
- Recognize thermal limits on branch elements and have a flow constraint feature.
- Be capable of optimizing both shunt and series compensation.
- Be capable of maximizing or minimizing real or reactive on defined interfaces for transfer studies.
- Have generation cost and load dropping objective function features.
- Be capable of scaling loads up or down.
- Be capable of load dropping uniformly by zone or optimally by bus.
- Have a "soft limit" feature for branches and generators to aid in convergence.

All of these features may not be available in a single program. However, having them will allow the planning engineer to customize use of the OPF to achieve desired results. As these programs become more mature and user-friendly, they have the potential to save a utility substantial capital investment and considerable engineering time. As a result, a utility using OPF can become more competitive in a rapidly changing, deregulated power industry.

SOME EXTENDED APPLICATIONS OF OPF

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OPF calculations have become reliable enough for practical use and are starting to take their place among the standard power system analysis tools. They are also becoming employed as components of more complex processes. The

present brief note comments on a few such processes with which we have recently had some experience. All of them involve contingency constrained OPF.

Simultaneous Transfer Capability Evaluation (TRACE)

Maximum transfer calculations have traditionally been non-simultaneous. They have typically been modeled with one degree of optimizing freedom. Then the “maximum” transfer between a company and any one neighbor (not necessarily directly connected) can be found without formal optimization merely by stepping through successive ac or dc power flow solutions, monitoring the pre- and post-contingency constraints for violation. Convenient nomograms can then be constructed to show how the company’s transfer limits with the neighbor change for different “coincident transfers”. Except in very simple cases, this kind of analysis gives little information about a company’s ability to import or export power simultaneously with multiple neighbors, that is, the overall transmission capacity of its network.

Simultaneous transfer capability can be evaluated as a true optimization problem using a dc network model together with linear programming. However, this level of modeling accuracy can be dubious, and since VARs and voltages often determine MW transfer limits, the results could be dangerously optimistic. An EPRI-sponsored development project addresses the more generalized TRACE formulation, based on an ac-modeled security constrained OPF (SC-OPF) problem. One of the requirements is to be able to handle a large contingency list, and to identify the critical contingency cases in it. This involves iteration between fast Security Analysis and SC-OPF. A challenge is how to present the results of a problem with more than two degrees of optimizing freedom. The limiting constraints themselves now tend to come in groups, rather than one at a time. The calculation has important applications in both planning and operation, including the support of transaction and reserve decisions.

Transmission Oriented Production Simulation (TOPS)

Production simulations over the last years have incorporated linearized MW transmission constraints in the form of network flow or dc power flow models, usually with very approximate loss representations. If MW transmission is at all affected by voltages and VARs, the results using oversimplified models can be very misleading. Hence is the trend toward modeling the true operational capability of the power system by incorporating a contingency constrained ac OPF calculation. This brings the need for much more data, to realistically model reactive sources and loads, and voltage regulating devices and their schedules. Situations where transmission limitations prevent the load from being fully supplied will naturally occur, and the OPF process has to recover from them. It must commit generation, curtail load, and modify the hydro schedule as appropriate, to avoid voltage collapse and comply with transmission constraints. It must feed back the results and the costs to the main simulation process, possibly iteratively, at each simulation interval (typically one hour).

Capacitor Installation.

The sizing and location of new capacitors, to ensure a defined level of steady-state security for a given base-case operating condition, is easily expressed and solved as a contingency constrained OPF problem. The capital cost of capacitors becomes the objective function, to be minimized by adding capacitors (or even reactors) at one or more of the candidate sites, as needed to comply with pre- and post-contingency operating limits. The process can be completely automatic, or can include interactive engineering participation, for instance to choose between similarly-priced alternatives. It is also possible to include in the selection criteria the effect of the new capacitors on transmission losses. A challenge then is to embed this kind of OPF solution within a multi-year planning process that considers variations in system load, generation and topology.

Transmission Service Pricing.

Comprehensive marginal costs can be computed at the solution of any OPF calculation. The OPF algorithm sometimes provides these costs directly, as in LP-based methods. With other algorithms, a separate marginal cost calculation process may be needed. Transmission-constrained marginal costs can be obtained for quantities including binding power system operating constraints, power production capacities, equipment regulation limits, area interchanges and transactions, losses, and bus powers. In particular, the incremental costs at load buses (singly or in clusters, zones or areas) measure the marginal costs of transmission constrained power delivery. Spot pricing approaches can use such OPF marginal cost results directly. Even the cost of MVAR supply and delivery is being addressed by utilities [A].

Marginal costing is small-perturbation sensitivity analysis. Alternative large perturbation approaches to the pricing of transmission congestion equally rely on OPF calculations. For example, the costs of the transmission constrained OPF solutions can be computed and compared with and without a postulated change, such as a specific transaction. A great deal more OPF-related work in this field is bound to be done.

Concluding Note:

OPF as used here refers to a problem only superficially resembling a smooth-functioned, nonlinear programming, formulation. Many models and constraints are discontinuous, sometimes intricately so. Others cannot be expressed in analytical form at all, such as certain indispensable engineering sanity checks. An example is the electrically ineffective control test: if the controls have little electrical (as distinct from cost) sensitivity to a particular quantity, they must not be allowed even to try to alleviate or prevent its violation, otherwise massive and impractical scheduling can occur.

[A] N. Dandachi, M. Rawlins, O. Alsac, M. Prais and B. Stott, “OPF for reactive pricing studies on the NGC system”, IEEE PICA Conf., pp. 11-17, Salt Lake City, May 1995.

APPLICATION OF OPF IN DEREGULATED ELECTRICITY MARKET

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Utility deregulation heightens the incentives for optimal deployment of resources in the competitive electricity market (EM). This section presents requirements for the EM that may be addressed by OPF and its extensions.

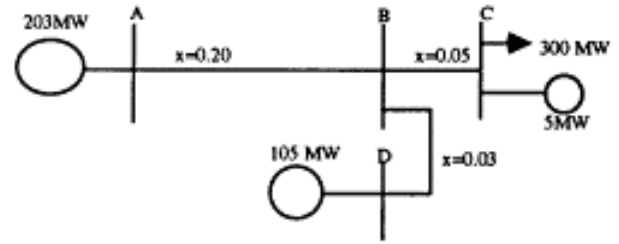
Bulk power transmission, which appears to have characteristics of a natural monopoly, is a major source of technical complication in a deregulated competitive market. The effect of parallel flows on transmission capacity is a classic example that illustrates the complications caused by having to share critical resources that (1) have limited capacities, and (2) exhibit behavioral characteristics that are governed by physical (e.g., Kirchoff's) laws which are not readily administered by business contracts. OPF enters the scene with its explicit recognition of network characteristics within the broader context of power system optimization.

Salient characteristics of the EM that are particularly relevant to OPF include:

- Requirements for comparability and transparency: The principles of comparability and transparency encourage usage of 'formalized' and 'systematic' tools and procedures, which are inherent in applications such as OPF.
- Price-based Competition: Successful competition requires optimal utilization of resources. OPF as a constrained optimization tool supports profit maximization, cost minimization, and constraint enforcement for broad classes of market activities.
- Open transmission access: Enforcing transmission security, allocating transmission capacity and pricing transmission services are key elements in a robust EM. OPF incorporates capabilities of the power flow, for explicit representation of the transmission network, within the formulation of a constrained optimization problem, to address open access issues.
- Unbundled services: Ancillary network services, such as voltage/VAr support, are being identified as part of the EM. OPF can assist with analyzing characteristics of the unbundled service components, defining market rules, and developing strategies for market participants.

Depending on the flexibility of their design and implementation, some existing OPFs may be used to address many of the above requirements. The following are simple examples that illustrate some

basic concepts.



| | Loss Factors | | | Incrom. Cost (\$/MWh) | | | Ap/L.F. | | | MW Losses | | | Cost | |
|-------|--------------|-------|-------|-----------------------|-------|-------|----------|----------|-------|-----------|--------|------|--------|--|
| | Bus A | Bus B | Bus C | Bus A | Bus B | Bus C | Bus A | Bus B | Bus C | Est. | Solved | Est. | Solved | |
| Bus A | 0.933 | 3.02 | 3.24 | 300 | 13.40 | 13.40 | \$713.45 | \$713.45 | | | | | | |
| Bus B | 1.017 | 3.29 | 3.24 | 310 | 13.87 | 14.01 | \$645.05 | \$645.39 | | | | | | |
| Bus C | 1.057 | 3.42 | 3.24 | 290 | 12.83 | 12.87 | | | | | | | | |
| Bus D | 1.010 | 3.27 | 3.24 | | | | | | | | | | | |

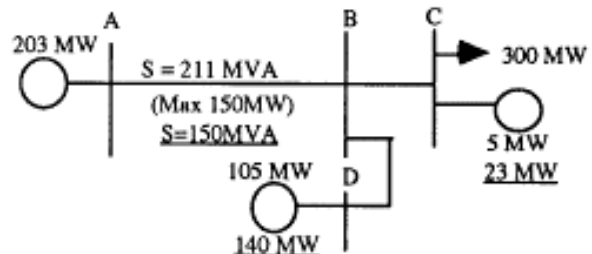
Economic Dispatch (w/o network security constraints)

Figure 1: Economic Dispatch

Figure 1 shows the familiar equal- λ condition at the optimal solution. In competitive bidding situations, the loss factors can be used to recognize location-specific characteristics of the bids. The concept is the same as in conventional ED, but merely (re-)interpreted under the context of competitive EM. Figure 1 also suggests the possibility of estimating changes in system quantities (e.g. losses, production costs) caused by changes in other parameters (e.g. load at bus 3). While the estimates would contain much higher errors for practical systems, they nevertheless represent potential alternative or supplement to repetitive solution of the complete problem each time something changes.

Constrained Economic Dispatch (with line flow constraint between bus A and B)

Figure 2 shows enforcement of LineAB limits. It represents a formal mechanism for MW flow curtailment that is based on formal modeling and analytical procedures. The example shows that, as a result of the binding security constraint, multiple bus λ 's were introduced into the system. Change in λ 's from the un-constrained case (Figure 1) were not easily predictable, thus highlighting the need to be careful when estimating and interpreting the lagrange multipliers (dual variables). Cautionary remarks notwithstanding, the dual variables nevertheless contain valuable information that should not be casually dismissed - the simple example brings out the formal relationships between the lagrange multipliers associated with bus injection and the constrained line flows. The relationship can be used as a basis for assessing the impact of network congestion in the comprehensive model for nodal pricing.



| | Increm. Cost (\$/p) | λ /p/ L.F. | C-Load 310MW | C Load 290MW | C-Load | Costs Est. | Solved | Constraint costs (\$/MW) |
|-------|---------------------------|-----------------------|-----------------|-----------------|--------|---------------|--------|--------------------------------|
| Bus A | 2.45 | 2.62 | 146MW | 146MW | 300MW | - | \$679 | (unconstrained) |
| Bus B | 3.87 | 3.80 | - | - | 300MW | - | \$713 | 1.17 |
| Bus C | 4.02 | 3.80 | 26MW | 16MW | 310MW | \$673 | \$674 | 1.28 |
| Bus D | 3.83 | 3.79 | 147MW | 134MW | 290MW | \$753 | \$754 | 1.07 |

Figure 2: Constrained Economic Dispatch

Constraint Modeling

OPF enforces constraints to some user specified limits (input) by optimally adjusting the solution variables (e.g. redispatch MW generation). OPF also calculates lagrange multipliers that are cost sensitivities for a unit change in each of the binding constraints. For the problem as shown in Figure 2, enforcing lineAB to 150 MVA produces a lagrange multiplier ($\mu=1.17$). Based on this μ we can estimate the effect of +/- 10 MVA changes to the limit value. Figure 3 shows the estimated results and compares them with those from re-solving the complete problem at the new limits.

| MVA Limit | Mu | Costs Est | Solve d | A | Bus MW B | Injection C | D |
|--------------|--------|--------------|------------|-----|-------------|----------------|-----|
| >211 | - | - | \$679 | 203 | 0 | 5 | 105 |
| 160 | .964 | \$701 | \$703 | 156 | 0 | 20 | 134 |
| 150 | 1.17 | Ref. | \$713 | 146 | 0 | 23 | 140 |
| 140 | 1.38 | \$725 | \$726 | 136 | 0 | 26 | 146 |
| [159] | [1.0]* | | | | | | |
| [184] | [0.5]* | | | | | | |

*--input Mu, output limit values.

Figure 3 OPF Constraint Enforcement

The traditional views on constraint modeling as described above can be extended to answer questions that may become more common in the deregulated environment.

“How many MVAs can be transmitted across LineAB if I was prepared to pay a premium of \$1.00 per MVA? or \$0.5 per MVA?”

It’s interesting to compare the above with the more classical view of: “LineAB has a capacity limit of 150 MVA. Now let’s calculate the impact of different limits.” The two views are complementary. Together, they provide a much more comprehensive set of functions than either could not on its own.

CHALLENGES TO ON-LINE OPF IMPLEMENTATION

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This brief note presents a few specific operational requirements and challenges that need to be met for a successful implementation and use of an on-line OPE package. Meeting these requirements will help the OPF technology in becoming a standard tool in an EMS environment either leading to specific stand alone power flow analysis software tools or to components of more complex

operational processes.

Robustness: An OPF program must produce consistent solutions if it is to be used to guide the decision-making of power system operators. This requires that the OPF solution not be sensitive to the (arbitrarily or randomly) selected starting point used and that changes in the solution point be consistent with changes in the operating constraints. There are several possible reasons for potential sensitivity of an OPF solution to initial starting points. Among them: (a) there are multiple local minima in the feasible region, and it is these different local minima that are reached from different initial points and (b) the solution method is unable to reach a true optimal solution.

If (a) is the reason, then the problem may lie in the nature of the actual power system. Usually adding the proper models and the operating information needed to fully specify the problem would eliminate the non-uniqueness. If, as in (b), the solution method is unable to reach a true local or global minimum, then the problem may lie with the OPF program used, or may even be due to an inherent limitation of the solution methodology chosen, and is thus more serious. Numerous robustness tests on the PG&E system strongly suggest that OPF solutions are insensitive to starting operating points [1]. Based on this experimental evidence, it seems reasonable to accept the premise that in the normally feasible region the OPF solution is unique, i.e., the OPF solution space is convex. We acknowledge that this can only be an empirical, rather than a rigorous theoretical conclusion. Yet it is a conclusion of great practical significance, for such convexity is a necessary condition for robustness. We consider this to be of vital importance to the ultimate acceptability of the OPF.

Expansion of the Scope of the OPF Problem: The OPF function has to calculate practically implementable control moves that steer the power system as reliably and as far as possible in the direction of the optimum, while avoiding and alleviating limit violations. All relevant constraints (more than is now typical) must be included in each OPF formulation. Also several requirements need to be met for an OPF to be able to produce practical solutions. Efforts to incorporate some of the above requirements in OPF applications have produced some benefits but more extensive testing and experience is needed.

A few of the additional OPF related requirements include: more flexible control and constraint priority strategies; incorporation of control and load dynamics; inclusion of start-up/shut-down constraints of certain controls and other operating constraints that meet specific practical requirements; hydro modeling; implementation of voltage stability and other dynamic constraints suitable for on-line environments; modeling of non-linear and voltage dependent loads; coordination of controls with different response characteristics; modeling of prohibited operating zones on the cost curves; effective modeling of the external system suitable for optimization applications; time restrictions on control/constraint violations; cost penalty thresholds on an

individual basis for constraint enforcement (this is becoming increasingly important as utilities move toward more competition and security under some conditions will be traded off for economy); effective branch switching modeling; other system specific operational requirements that each utility should identify and develop for successful OPF implementations.

Ineffective “optimal” rescheduling: Existing OPF algorithms use all available control actions to obtain solution, but for many applications it is not practical to execute more than a limited number of control actions. However, it is not possible to select the best and most effective set of a given size from existing OPF solutions that uses all controls to solve each problem. Each control facility participates in both, minimization of the objective function and enforcement of the constraints. Separation of the two effects for evaluation purposes is not possible.

One possible definition could be to include the total number of control actions, or the limits on the number of control actions for each control class in the formulation. Another definition could be to assign an initiation cost for each control action whose number needs to be limited. In this case, the minimum cost solution, including the starting costs of control actions, would produce the correct number of actions. Neither definition, however, can directly lead to acceptable solutions. Lately, fuzzy set methods have been proposed to curtail ineffective control actions. Preliminary results seem to be promising but further work is needed for implementing fuzzy based methods that can lead to robust solutions. The compromise in the short run should be to rely on near-optimal solutions that incorporate sound engineering rules that are fast enough for practical applications. In the long run a solid methodology to address this problem is very much needed.

Discrete modeling: The OPF problem is discrete in nature. Presently, most OPF algorithms treat all controls as continuous variables during the initial solution process. Once the continuous solution is found, each discrete variable is moved to its nearest discrete setting. This procedure gives acceptable solutions provided the step sizes for the discrete controls are sufficiently small, which is usually the case for transformer taps and phase shifter angles. However, shunt capacitors and reactors with larger bank sizes usually have greater impact on the optimization. Currently, two different approximation approaches are used after the rounding off: One is to execute a conventional power flow solution with all the discrete variables fixed on their steps. The other is to solve the optimization problem again with respect to the remaining continuous variables using the first continuous solution as the initial point. The former approach is widely used because of its computational efficiency. The latter approach gives a better solution in terms of feasibility and minimization, but the second optimization significantly increases the total time for an OPF execution. The final

solution is still not guaranteed to be optimal because incorrect values for the discrete control steps may have been selected.

Given the intractability of rigorous solution methods, approximate solutions that can produce near optimal results appear to be a reasonable alternative. The use of penalty functions for discrete controls is one such scheme [21]. Substantial more work is needed to effectively resolve all problems associated with the discrete nature of controls and other discrete elements of the OPF problem.

No serious attempts have been made yet in implementing 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 are altered may inadvertently create new problems. In general, the trajectory is probably less important for thermal violations than for voltage problems.

The limited amount of time available to correct constraint violations is 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. For example, generator ramp rates 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.

Consistency of OPF With Other On-Line Functions: On-line OPF programs are implemented in either study or closed loop mode. In the study mode, the OPF solutions are presented as recommendations to the dispatcher. In the closed loop mode, the control actions are implemented in the power system, typically via the SCADA system of the EMS. A major problem of an OPF in closed loop mode is the design of its interface with the other on-line functions which are executed with different periodicities. Some of these functions are: Unit Commitment, classical Economic Dispatch (ED), Real-Time Sequence, Security Analysis, Automatic Generation Control (AGC), etc. To reduce the discrepancy between idealized and realistic OPF problems, emphasis should be focused in establishing consistency between these functions and static optimal solutions produced by the OPF. Consistency requires proper interfacing and integration of the OPF with these functions.

A central aspect of consistency between the OPF and other on-line applications is the coordination of the OPF-ED-AGC control hierarchy. The overall objective here is how to impose the security constrained MW schedules produced by an OPF to AGC through the ED. In the past simplistic approaches were implemented with limited success. A promising approach is to install a security constrained economic dispatch (SCED) which plays the combined role of OPF and ED for the active power subproblem. Substantial effort is required to implement SCED in "closed loop" mode where base points and participation factors are passed automatically to AGC. This will be a very important step toward implementing a secure automatic generation control. A similar concept can be developed for the reactive power problem, where target setpoints produced by a transmission loss objective are passed to a real-time reactive dispatch that schedules voltages at key buses in the system.

Recent regulatory changes to open up electric power transmission networks to foster competition and customer choice have touched off a debate over how the transmission system should be restructured to facilitate open access. Independently of the outcome of this debate it is certain that the need to include transmission considerations in scheduling and production simulation studies will substantially increase. This calls for implementation of transmission oriented scheduling and production simulation models. The OPF solver in various forms should be the basic tool for modeling the true operational capability of the power system in these processes. Embedding the OPF solver in these models is a formidable task placing onerous requirements in system modeling, data handling and methodology development.

Concluding Note:

On-line implementations pose the most onerous requirements on the technology. Classical formulations expressed in smooth nonlinear programming form are far too approximate descriptions of the real-life problems to lead to successful online implementations. Substantial progress has been made in modeling operational and security considerations in a realistic manner but a great deal more work is needed in implementing OPF-based models that will either lead to specific stand alone power flow analysis software tools or to components of more complex operational processes. In this note only a few specific requirements that need to be met for a successful implementation and use of an on-line OPF package were briefly presented.

References:

- [1] A.D. Papalexopoulos, C.F. Imparato and F.F. Wu, "Large-Scale Optimal Power Flow: Effects of Initialization, Decoupling and Discretization," *IEEE Transactions on Power Apparatus and Systems*, Vol. PWRS-4, pp. 748-759, May 1989.
- [2] E. Liu, A.D. Papalexopoulos, W.F. Tinney, "Discrete Shunt Controls in A Newton Optimal Power Flow," *IEEE*

Transactions on Power Systems, vol. 7, No. 4, pp. 1519-1528, Nov. 1992.

CONTROL APPLICATIONS OF THE OPF IN EMS

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Introduction

The Optimal Power Flow algorithms are much faster and more robust than in the past. Using OPF, real time control will improve both security and economy of system operation. Two problems arise: first, the need for a more robust and faster OPF algorithms: second, and not less important, how to apply OPF practically in truly real-time mode?

The robustness and performance requirements are mainly a question of system modeling and algorithms. They may be met. However, the integration of OPF into EMS, is more challenging. Data collection may be fully automated rather easily, but in order to apply OPF results to the power system, two very different approaches may be chosen: either to let operators apply the OPF results manually, or to apply these results automatically. In the first approach, at least in large scale systems, the operator is a bottleneck and special OPF solutions must be provided, not optimal, but moving few control variables at the same time. In the second approach, the interface between OPF and power system automatic control must be designed carefully, and OPF algorithms must be more robust for continuous automatic operation. Among these two approaches, the second one is more desirable. The main difficulty in applying OPF in real-time is its static nature. It assumes given loads, constant frequency and voltages. The automatic controls in power systems deal with dynamics and transients taking generating unit inertias and magnetic properties into account. So, in order to apply OPF results through automatic controls, the relevant interfaces must be designed without perturbing the dynamics, especially for active powers.

OPF in Automatic Active Power Generation Control

The standard implementations of OPF function in the real-time active generation control (AGC) are based on a combination of a full OPF referred to as Security Dispatch (SD) and a classical Economic Dispatch (ED) or Constrained Economic Dispatch (CED) [1]. In these implementations SD uses the State Estimation (SE) solution as a base case and reschedules generation whenever a branch overload occurs. For each unit where rescheduling occurs new critical constraints, sensitivities and limits are provided to CED. CED calculates, at a rate equal to the rate of execution of a classical ED, the new unit base points and secure and economic participation factors. CED optimizes the cost of

generation subject to the critical network constraints as identified by SD. It also provides secure and economic participation factors to Load Frequency Control (LFC), so that between consecutive CED executions no incorrect control actions are issued by LFC. Normally, in AGC only on-line data for unit generations and tie-line flows are available. Because of this limitation and some restrictions on CED modeling numerous assumptions and approximations had to be made [1].

CED is typically executed every 3 minutes, however during periods of rapid load change, execution may be initiated every 30 seconds. The major improvement in modern EMS real-time environment is a SE function running at the SCADA scan rate frequency, which enables SD to be executed at the frequency of CED. Also the branch flow constrains and load changes are accurately modeled and tracked. In addition, it is possible to run contingency constrained optimal power flow (CCOPF) and produce a set of critical contingency constraints and sensitivities to be included in SD. All previously required approximations and problems related to the standard implementation of CED are eliminated. However, this solves only part of the problem. In order to perform automatic real-time control in closed loop mode, it is necessary to resolve control issues and interfaces with control process implemented in LFC. For example, LFC moves the units along trajectories that combine Area Control Error (ACE) with economic operation. Integral (over time) type of control may be required instead of base unit points and secure participation factors. The present CCOPF techniques are fast enough and reliable to solve SD at CED frequency, while the present CCOPF techniques do not satisfy all functional and performance requirements.

The definition of system security in actual power system operation is varying among different utilities. One of the widely used security concepts is the so called n-1 security criteria. In order to satisfy the n-1 security criteria the power system should be secure (no violations) after any single contingency. However, this criterion is conservative, because it does not take into account the system corrective capabilities after the outage has occurred. By introducing corrective rescheduling in the n-1 security concept, two very different approaches to CCOPF implementations can be defined:

- *all preventive control
- *preventive/corrective control

There are obvious differences between these two approaches. The preventive formulation offers a higher level of security, but at the same time CCOPF problem is more constrained than the preventive/corrective concept. As a result the system operating cost is much higher if the first concept is applied. Also, the first formulation is more prone to infeasibility. The preventive/corrective formulation although less constrained requires a significantly larger optimization problem to be solved. The CCOPF function in any of these two cases is time consuming. The performance problems are dealt with by introducing in the model a relatively small number of critical contingencies. This

approximation worsens an unresolved problem for all CCOPF formulations that is: by fixing just a small subset of most critical contingencies there is no any guarantee that other contingencies labeled as noncritical will not become critical after a new CCOPF solution. The only practical solution to this problem is to directly involve a large number of critical contingencies in CCOPF formulation. The preventive/corrective control concept should gain operators' confidence especially in the case when the preventive mode control requires expensive rescheduling of the base case generation. This problem will become more serious in deregulated environment. Developing a fast and robust CCOPF algorithm to handle the de-regulated power systems requirements is a challenge. In this area it may be required to investigate other available optimization techniques like newly developed interior point based algorithms. Another area of further research and development will be interface of CCOPF with CED. The major question is what kind of information to pass from CCOPF results to CED and how often. Having in mind the relatively long execution time of CCOPF it is required to significantly improve performance of the CCOPF algorithms in order to be able to use its result in real-time control. Another area of interest is how to introduce Voltage/VAr related problems in CCOPF formulation and how to coordinate resulting active and reactive control actions. All these aspects are challenges for OPF technology in near future. In a new de-regulated environment we can expect utilities to be involved in more power transfers and wheeling transactions. Often this will result in higher loading of the transmission network which results in worsening security problems. Both transmission overloads and voltage problems will be more difficult and more expensive to solve. Additional tools will be needed to evaluate costs incurred by rescheduling systems to satisfy security constraints violated by increased power transfers.

OPF in Automatic Voltage/VAr Control

Voltage/VAr control is essential in both normal and emergency operation of power systems. In normal operation the control aims at an economical supply of power to the consumers. This is achieved through satisfying bus voltage constraints while maintaining minimum network losses. For voltage and reactive power control, transients are linked to the electromagnetic flux and no longer to the mechanical inertia of rotating machines. So, dynamics accept step changes of control set points (coming from the static model) in a much easier way than in the active power control. Voltage/VAr problems are usually localized in a power network. Because of high reactive power losses and related bus voltage drops, reactive problems can be efficiently handled only by local reactive controls. During emergencies, lack of reactive power and voltage support may lead to major disturbances often referred to as voltage collapse. This problem must be considered in real-time Voltage/VAr control. Automated real-time voltage control, in the global optimized sense, is not yet in wide use even though there is an acute need for it to achieve secure economic power system operation.

The standard practice of real-time Voltage/VAr control in EMS is described in [2]. In this concept a predefined priority sequence is applied to the control objective, depending on the “security” level of the system operating state. The first control objective is to remove the bus voltage limit violations and to minimize those violations that cannot be eliminated using the Reactive Security Dispatch (RSD) function. The second objective is to minimize the system active transmission losses. Usually the results of reactive optimization require to move a significant number of reactive controls, most of them with an insignificant effect on the optimal solution. If Voltage/VAr control is not automatic this kind of result is practically useless. In order to eliminate this problem different techniques can be used. For example, in LP based OPF algorithms this can be resolved by using “V” shaped cost curves with the same absolute slope on either side of the origin. This will result in a so called “minimum number of controls” suboptimal solution. This is not necessary in an automatic control environment.

Although bus voltage violations are considered a useful measure of reactive security of the system state they are just one of many relevant indications of Voltage/VAr problems. A simple extension of this criterion will be to monitor reactive reserve in the system, on the system level and/or individually for controlled areas. However, these are all simplified indices used to detect potential voltage stability problems. In an improved control scheme the reactive security of the system would be checked not only by monitoring the bus voltage limits and reactive reserve in the system, but also by using OPF function to calculate the loadability of the system as a measure of voltage stability margin. Also, it is necessary to modify the objectives of RSD and Loss Minimization functions in order to cope with voltages stability problems.

All automatic voltage control devices have local control logic to maintain voltages on values sensed at their specific locations. As the system conditions change, the set points at these local voltage controllers have to be adjusted often on hourly basis. Voltage/VAr problems, inherently nonlinear, are very difficult to solve by operators regularly especially in non-predicted situations. Thus, it is very attractive to implement an automatic real-time Voltage/VAr control function. Although many important pieces of this function are already available, there is still a significant amount of work to be done. For example, the following issues have to be resolved:

- * The current concepts will require improvements in detecting, modeling and resolving voltage stability related problems using existing OPF algorithms
- * The overall concept of reactive security has to be further improved and appropriately modeled in SA and OPF algorithms,
- * The contingency constraints are not considered at all and this is an area in which intensive research is required. Existing methods for voltage stability assessment and control are very time consuming and not robust enough to be implemented in a real-time environment

- * The problem of control system algorithm (PI or PID control, setpoints or incremental control (raise- lower) pulses signals). needs to be studied,
- * The voltage dependency of loads
- * The effects of static characteristics of voltage regulators (AVR on generating units, AVR on LTC transformers)
- * The accurate modeling of VAr limits on generating units $Q=f(V,P)$
- * The coordination of the controls with different response time and dynamic characteristic
- * The problem of control signals for generating units (reference voltage set-points or reference reactive injection set-points)
- * The stability of control algorithm
- * The interface to the SCADA and modification of the SCADA to allow similar functionality available in LFC for reactive control devices.

The Voltage/VAr problems will be more important in the near future due to lack of transmission capability for accommodating the increasing loading of transmission network as a result of open access and de-regulation act. Multiple simultaneous transactions will greatly increase the vulnerability of transmission networks to voltage stability problems. Although, these problems can be resolved with an increase in reactive compensation especially at low voltage levels, that solution requires relatively high investment. A sophisticated automatic real-time voltage control can significantly improve the capability of the existing control devices and transmission facilities to operate securely under expected large and fast changing loading of transmission networks.

Voltage stability problems are becoming more acute with higher loading of the transmission network and increased transfers of active power. There is need for comprehensive set of tools to deal with these problems, especially for an early detection of voltage stability problems. OPF can play an important role in such a tool. There are methods to calculate loadability margin of the system using OPF algorithms. This may be added to the existing tools for security assessment and as a part of real-time voltage control. Much more needs to be done in developing tools for contingency simulation in light of potential voltage stability problems. Other major challenges include preventive control strategies for voltage stability problems with and without contingencies. Overall concept of CCOPF is well defined for active powers, but is still in an early research phase for voltage stability related problems. All these issues have to be addressed. Another major question is how to coordinate control actions aimed at resolving active power related

problems (mainly transmission line overloadings) and control actions aimed at resolving voltage stability problems? Do we execute and implement these control actions independent of each other or do we have to use a new tool with simultaneous simulation and resolving of both problems? This area represents major challenge not only for OPF function but also for other network analysis applications.

Conclusion

Is it feasible to implement OPF in an automatic (closed loop) control mode in EMS? The answer is yes, but many elements involved must be improved. Optimal power flow algorithms must be improved further to be unconditionally robust. An OPF algorithm will never be too fast, further improvements in performance are always welcomed. Significant improvements in problem formulation and power system modeling have to be made for real-time implementation of optimal voltage control and CCOFP. OPF algorithms have to be improved to deal with voltage collapse problems and corrective controls to eliminate or reduce the risk of voltage collapse. Interface between EMS functions involved have to be carefully designed and improved. Especially control devices and algorithms dealing with Voltage/VAR control have to be defined and integrated in the existing SCADA environment. In the existing EMS environment one of the major requirements is to provide a scan rate State Estimation. This will greatly improve control process by providing the latest base network solution which allows for accurate modeling and tracking of system conditions and changes.

References

- [1] R. Bacher and H.P. Van Meeteren, "Real Time Optimal Power Flow in Automatic Generation Control," IEEE Transactions on power Systems, Vol. PWRS-3, pp.1518-1529, Nov. 1988.
- [2] S.K. Chang, F. Albuyeh, M.L. Gilles, G.E. Marks and K. Kato, "Optimal Real-Time Voltage Control," IEEE Transactions on Power Systems, Vol. PWRS-5, pp. 750-758, Aug. 1990

CONCLUSION

Interest in OPF confirms its potential ability to handle preventive corrective control measures, incorporate contingency/constraints and automatically schedule voltage/ VAR control in the EMS system. Extension of OPF usage and their economic/technical challenges for VAR planning, transfer capability pricing in the open deregulated utility environment have been discussed.

To make OPF of the future attractive to the industry and users, the learning curve must be reasonable, complexity of OPF

algorithm must be reduced, and finally the OPF programs must be user friendly. Diagnostic checks of errors in programming or system errors should be readily available to inexperienced users.

Based on the panelists' comments and industry/ developer experience the limitations and promise of OPF continue to pose challenges to the power industry. As more people use available tools and the cost benefit of the tools are realized, we hope to simplify and generalize OPF as an optimum allocation/scheduling tool of the future.

ACKNOWLEDGMENT

The authors wish to thank the members of the working group on operating the economics. We are indebted to Dr. M. E. El-Hawary, chairman of the working group, for his kindness and leadership that led to the panel. We also thank the staff of CESaC for their support in putting this paper together.

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