PSERC

Coordination of Transmission Line Transfer Capabilities

Final Project Report

Power Systems Engineering Research Center

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Final Report

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Power Systems Engineering Research Center

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Executive Summary

The maximum power that can be transferred over any transmission line, called the transfer capacity, is limited by constraints on thermal limits, voltage bounds, and security considerations. As the power system gets more stressed with increasing loads, the need to transfer power over long transmission lines is becoming very important. This is especially the case for deregulated markets where it is attractive to minimize costs by buying power from remote generators with lower generation costs.

In the present power system operation, the transfer capacity studies of transmission lines are carried out separately by their owners with little coordination. The objective of this project has been to propose a global framework for coordinating the capabilities of several transmission paths, while also meeting the regulatory requirements on voltage security and dynamic security. As an example, we focus on maximizing the transmission capacity of the California-Oregon AC Inter-tie (COI), by coordinating other path-flows that have an impact on the COI capacity. We show that substantial improvements in the COI MW transfer can be achieved with reasonable rescheduling of neighboring tie-line flows using the optimization algorithms presented.

These coordination algorithms would be of vital importance in stressed power-flow scenarios when there is a need to increase the capability of one or more critical transmission lines by rescheduling of other paths, while also satisfying strict requirements on system security. The optimization results could suggest operating procedures which could be entered into the transmission contracts appropriately. Also, by introducing the economic costs associated with specific path-flows, the optimization can be used for maximizing the profits of a specific path owner by approaching the problem in a global sense. This is because the optimization specifically points to those neighboring path flows which are limiting the capacity of the critical transmission path under consideration.

The computations involve four commercial software engines: 1) Bonneville Power Administration (BPA) Power-flow program *pf*; 2) Electric Power Research Institute (EPRI) midterm transient stability program *ETMSP*; 3) EPRI output and PRONY analysis program *OAP*; and 4) EPRI small-signal stability program *PEALS*. The coordination problem is formulated into constrained nonlinear optimization problems, and optimization algorithms have been developed as tailor-made solutions to this severe implicit nonlinear problem. The optimization is implemented in the form of Unix Shell routines, which interface with the commercial engines mentioned above. The programs were tested on few standard WSCC planning cases. These are realistic large-scale representations of the western grid consisting of about 1000 generators and

6000 buses. The project objective has been to demonstrate the feasibility of the computations for large-scale systems and computational efficiency was not a priority. Typically, the algorithms converged to near optimal solutions in a few iterations. The results are dependent on power-flow scenarios and on contingency cases being considered.

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1. Introduction

1.1. Summary

With growing consumer demands, large power exchanges over long transmission lines play vital roles in viable and economic operation of modern power systems. For example, the transmission paths from Northwest areas and western Canada to California played an important role in relieving the recent energy crisis of California. The maximum power that can be transferred in a reliable fashion over any transmission line is called the transfer capability [1], which is defined by NERC (North American Electric Reliability Council) as [2]:

- With all elements in service, all voltages and flows are within normal ranges
- The system remains stable after any single contingency, and
- After any single contingency, all flows and voltages are within emergency ratings.

In reality, the transmission transfer capability is limited by a number of various mechanisms, including stability, voltage and thermal constraints [3]. Different components and transmission paths in a large interconnected power system will also impact the transfer capability on some certain transmission paths. Based on such considerations, the document aims to presents a methodology to develop global strategies for the improvement and coordination of transmission line transfer capability. The document is organized as follows:

- Interconnected transmission system modeling in the western power grid (Chapter 2)
- Explanation and application of nonlinear programming algorithms (Chapter 3)
- Computational results and analysis for transient stability constraints (Chapter 4), voltage security constraints (Chapter 5), and small-signal stability constraints (Chapter 6)
- Brief introduction of economical aspects into this problem (Chapter 7)

1.2. Motivation

Transfer capabilities of inter-tie transmission lines establish how much power can be exchanged between the areas without compromising system viability, voltage security and dynamic security. From economic viewpoint and from ease of power system operation, it is nice to have large transfer capabilities since it relieves market pressure and also makes the dispatching of power more manageable for the system operators. With political and environmental restrictions on the development of new transmission and generation facilities, it is all the more significant to compute and coordinate the transfer capabilities accurately so that the system can be operated closer to the limits while also maintaining adequate system reliability.

There is always an inherent trade-off between increasing utilization of the grid and security of operation. Many research works have been carried out in the improvement of transmission transfer capability with a variety of operation constraints, such as stability, voltage security and thermal limits. A methodology is provided in [4] to examine the impact of transmission constraints on the efficient operation of large-scale power markets. The study in [5] aims to utilize some new technologies such as voltage instability predictor to raise energy transfer capability in certain corridors. Other research directions aim to utilize FACTS components such as SVC and TCSC to enhance certain line transfer capability.

In the current methodology, because these different transmission paths may belong to different owners, the operators only study their own system and corresponding actions are isolated without concerning the interactions between different systems. However, the modern electric system is a tightly integrated network, and as a result, the actions of a single entity impact multiple others. The flows on one transmission provider’s system will change the flows and resulting transfer capability of another transmission system and will impact the operation and security of other systems [6]. Therefore, it is impractical and insufficient to study the path transfer capability without the concern of the other connected systems.

In this research report, the coordination of transmission line transfer capability is proposed such that by controlling the system as a whole, a global optimization solution could be reached and the capability limiting components could also be identified. Moreover, such solutions make it possible for the transmission owners to maximize their transmission revenue without endangering system security and stability. Hence, it will also be of vital importance to economics. Specifically, our initial focus is for increasing the path transfer capability of California-Oregon Intertie (COI) by studying the relationship between the other transmission path capabilities in the western system and the COI transfer capability. Under stressed power-flow conditions in California, the framework of the report suggests how the other path-flows can be coordinated for increasing the COI path transfer power into California without endangering the overall system security.

The objective of our project is to develop strategies for coordination of transmission path capabilities in a large interconnected power system. The project is motivated by the transmission path capability studies in the western electric grid. We expect the project to develop “global” strategies for improving the path capabilities of key transmission paths such as COI by establishing the interactions of different path power-flows.

2. Project Tasks

2.1. System modeling

In any interconnected power system, it is known that all individual paths and subsystems must satisfy such regulatory criteria as acceptability or viability, voltage security, small-signal stability and transient stability. As a first step, our objective is to identify the transfer capability regarding these limits individually. In future research, the optimization process for each of these individual constraints could be combined into a universal path coordination software.

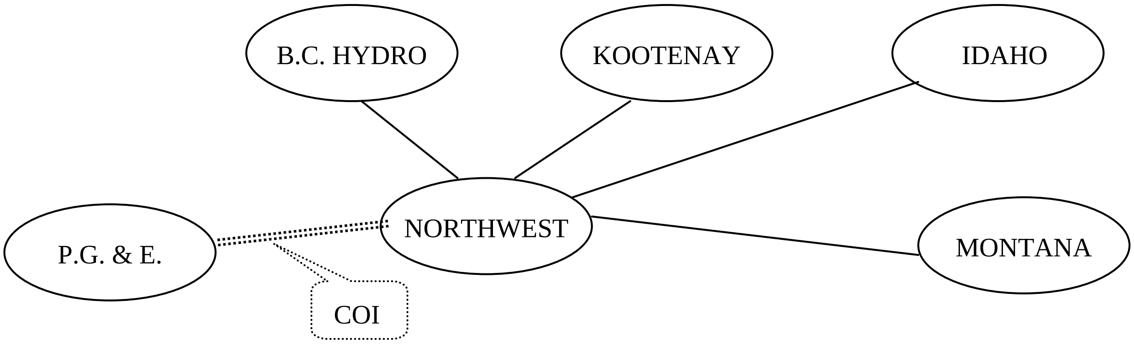

Fig 2.1 Illustration of Northwest and neighboring power grids

In this document, standard large-scale WSCC planning cases, namely, 1997 summer peak scenario, 1998 winter peak scenario and 1998 summer peak scenario of the WSCC system are studied. The cases consist of more than 1,000 generators and 6,000 buses. Although the path-flow coordination problem has been simplified (Fig 2.1) to focus on the COI path in this research project, it is apparent that the computation necessary for the coordination of line transfer capability is very intensive.

As we can see, to investigate the line transfer capability of COI from Northwest (NW) to Pacific Gas and Electric (P.G.&E.), four other transfer paths from Northwest to the neighboring areas B.C.HYDRO (BC), WEST KOOTENAY (WK), IDAHO (ID) and MONTANA (MT) should also be taken into account because these paths will directly interact with each other. We will show later how these paths affect the transfer capability of COI. On the other hand, by altering the power transferred in these paths, the constraints limiting the COI transfer capability can be improved and potential benefit can be obtained resulting from the generation redispatching in the corresponding areas.

2.2. Task description

Following tasks are set up in order to solve the problem step by step. During the progress of the research, some of them are modified to reflect on the problem statement.

- Task 1 – Formulate the problem in the parameter space, including constraints on A) path-flows, B) system resources, C) power-flow requirements (e.g. VAR reserves), D) inter-area mode damping requirements, and E) transient stability requirements
- Task 2 – Develop power-flow based optimization tools for optimizing the transfer limits of specific transmission path(s), satisfying constraints A), B), and C).
- Task 3 – Combine power-flow and small-signal stability tools for optimizing the transfer limits, satisfying constraints A), B), C), and D).
- Task 4 – Identify the critical system elements and transmission paths which constraint the optimal values in Steps 2 and 3. Study the optimal solutions in Tasks 2 and 3 as related to Constraint E) of Step 1.

2.3. Deliverables and project status

Following items were stated in the proposal as deliverables for the project:

- Optimization problem formulations.
- Preliminary methods for optimizing the transfer path limits under power-flow and small-signal stability constraints.

- Report test results of the methods on 1998 winter and 1998 summer western inter-tie large-scale representations.

This project began in Fall 1999. At present, the following steps have been accomplished.

- Formulation of the optimization problems.
- Study of voltage security, small-signal stability and transient stability constraints on California-Oregon Inter-tie (COI) path capability.
- Implementation of Task 2 on WSCC 1998 Spring peak case.
- Implementation of Task 3 on WSCC 1998 Spring peak case.
- Preliminary study of economic formulations.

3. Optimization Algorithms

3.1. Background

From the system model and preliminary analysis of the project in Chapter 2, the solution of concerned problem can be categorized into a nonlinear optimization process. Due to the complexity and intensive computation required, it is inevitable to introduce some efficient nonlinear programming algorithms. In this chapter, the standard algorithm, BFGS (Broyden-Fletcher-Goldfarb-Shanno) method and relevant techniques are discussed in detail. Multi-objective programming is also mentioned in the later part.

3.2. BFGS method

BFGS method is one of the widely used Quasi-Newton methods. The basic idea behind Quasi-Newton method is to retain the fast convergence speed of Newton method without evaluating the Hessian matrix [7].

For the following nonlinear programming problem:

$$\min_{p\in P} E(p) \tag{3.1}$$

The updating scheme for quasi-Newton is given as:

$$p_{k+1} = p_k - \alpha_k H_k \nabla E(p_k) \tag{3.2}$$

Where, $\nabla E(p_k)$ is the gradient vector of the objective function (3.1) at k-th iteration, which is computed by center differentiation (3.3).

$$\nabla E(p) = \left[\frac{\partial E(p)}{\partial p_i} \right]_{n\times 1} = \left[\frac{E(p + \Delta p_i) - E(p)}{\Delta p_i} \right]_{n\times 1} \tag{3.3}$$

Δp_i is taken to be from 1% to 5% perturbation value on i-th entry p_i of the estimated parameters. α_k is the optimal step length determined by line search at the k-th iteration. H_k is a positive definite matrix that can be adjusted according to (3.4).

$$H_{k+1} = (I - \rho_k s_k y_k^T) H_k (I - \rho_k y_k s_k^T) + \rho_k s_k s_k^T \tag{3.4}$$

Where

$$s_k = p_{k+1} - p_k \tag{3.5}$$

$$y_k = \nabla E_{k+1} - \nabla E_k \tag{3.6}$$

$$\rho_k = \frac{1}{\mathrm{y}_\mathrm{k}^\mathrm{T} s_k} \tag{3.7}$$

H_0 is an arbitrary positive definite matrix. The secant equation requires that the symmetric positive definite matrix H_{k+1} map s_k into y_k. This will be possible only if they satisfy the curvature condition

$$s_k^T y_k > 0 \tag{3.8}$$

In fact, condition (3.8) is satisfied automatically as long as the objective function is convex and the Wolfe or strong Wolfe conditions are imposed in the line search part. Thus, the initial value for H_0 is set to unit matrix. Moreover, it is easy to show that H_{k+1} is positive definite whenever H_k is positive definite and (3.8) is also satisfied. Thus, the convergence of the algorithm is guaranteed.

It is known that BFGS formula has very effective self-correcting properties. If the matrix H_k incorrectly estimates the curvature in the objective function in which the bad estimation slows down the iteration, then the Hessian approximation will tend to correct itself within a few steps. The self-correcting properties of BFGS hold only when an adequate line search is performed. In particular, the Wolfe line search conditions ensure that the gradients are sampled at points that allow the model to capture appropriate curvature information.

3.3. Wolfe conditions

Line search stage is the key part during the implementation of BFGS method, in which step length α_k is computed to guarantee the convergence of BFGS. Some conditions are adopted as the criteria for ending the line search stage [7].

A popular line search condition stipulates that α_k should first of all give *sufficient decrease* in objective function f, as measured by the following inequality

$$f(x_k + \alpha p_k) \leq f(x_k) + c_1 \alpha \nabla f_k^T p_k \tag{3.9a}$$

for some constant $c_1 \in (0,1)$. This condition is illustrated in Fig 3.1. The right-hand-side of (3.9a) is denoted $l(\alpha)$. The function l has negative slope as p_k is a descent direction, but because $c_1 \in (0,1)$, it lies above the graph of ϕ for small positive α. In practice, c_1 is often chosen quite

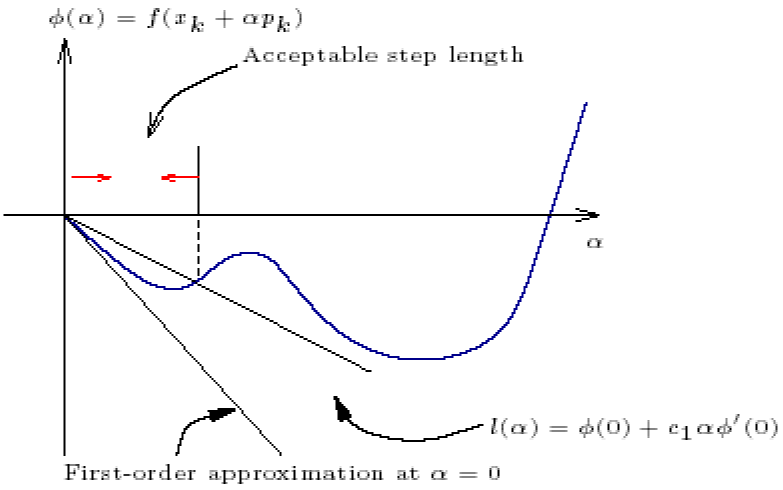

Fig 3.1 The Sufficient decrease condition

small, say $c_1 = 10^{-4}$, so even a small reduction in f will suffice.

To rule out unacceptable short steps, the second requirement — *curvature condition* — which requires that, α_k satisfies:

$$p_k^T \nabla f(x_k + \alpha p_k) \ge c_2 p_k^T \nabla f_k \tag{3.9b}$$

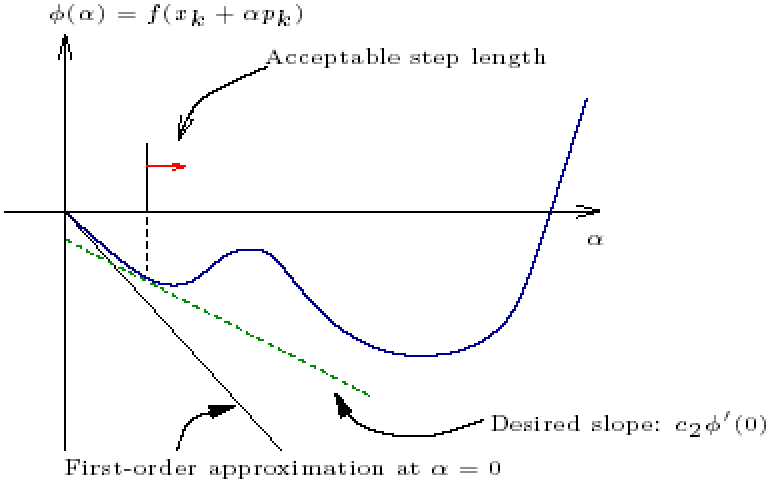

Fig 3.2 The Curvature Condition

for some constant $c_2 \in (c_1, 1)$.Note that the left-hand-side of (3.9b) is just $\phi'(\alpha_k)$, so the curvature condition simply ensures that the slope of ϕ at α_k is greater that c_2 times the slope of

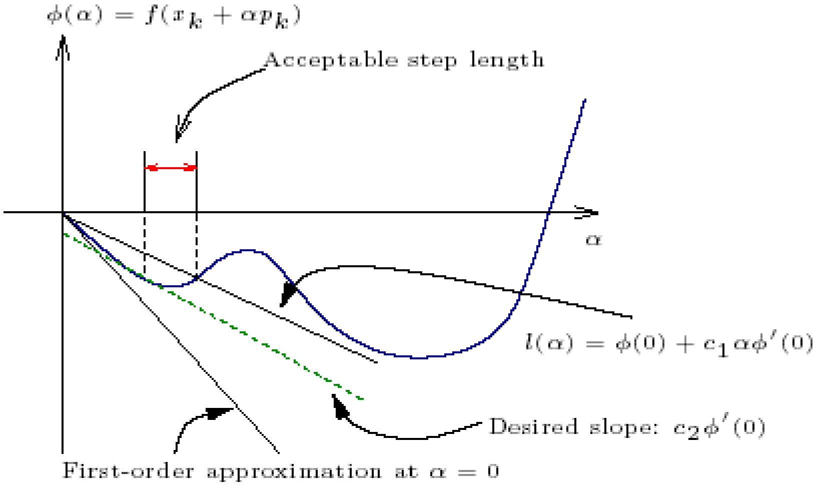

Fig 3.3 The Combined Wolfe Condition

ϕ at $\alpha = 0$. As the slope of ϕ is initially negative, this simply means that the graph has "flattened out sufficiently". Typical values of c_2 are 0.9 when a Newton-type method is applied. (3.9a) and (3.9b) are collectively called Wolfe condition, which are illustrated in Fig 3.3.

3.4. Related techniques in BFGS implementation

3.4.1. Penalty functions

Once some constraints are taken into account, their effect on the optimization solution should be included in the iteration. For example, if there is an upper or lower limit on the power generation within certain areas or in some certain power plant. We have to add the penalty term to the objective function as below:

$$E^p(p) = (p - p_l)' D_l (p - p_l) + (p_u - p)' D_u (p_u - p) \tag{3.10}$$

where

p: parameter vector

p_l: lower bound vector for parameters

p_u: upper bound vector for parameters

D_u, D_l: diagonal weighting matrix

By adding this option, "soft constraints" on the control variables, which could be violated within tolerable range, are set flexibly at the demand of the optimization problem itself.

3.4.2. Line search algorithms

In the last section, it was noted that certain curvature conditions should be satisfied to implement Quasi-Newton method [8]. In the line search stage, suppose a continuously differentiable function $f : R^n \to R$ and a descent direction p for f is known at a given point $x \in R^n$. Thus, if

$$\phi(\alpha) \equiv f(x + p\alpha) \ , \alpha > 0$$

Then an acceptable step α is defined:

$$\phi(\alpha) \le \phi(0) + \mu\phi'(0)\alpha \tag{3.11a}$$

$$|\phi'(\alpha)| \le \eta|\phi'(0)| \text{, where } 0 < \mu, \eta < 1 \tag{3.11b}$$

The motivation for requiring such conditions, which are collectively known as Wolfe conditions is very clear. If α is not too small, condition (3.11a) forces a sufficient decrease in the function. However, this condition is not sufficient to guarantee convergence, because it allows arbitrarily small choices of α>0. Condition (3.11b) rules out arbitrarily small choices of α and usually guarantees that α is near the minimizer of ϕ. In this way, we can guarantee that a positive definite Quasi-Newton update is possible. Usually the line search is done in two stages: A bracketing phase finds an interval containing desirable step lengths, and a bisection or interpolation phase computes a good step length within this interval. J.J. More and D.J.Thuente describe a line search algorithm that produces a sequence of iterates converging to a point which satisfies Wolfe condition and terminating in a finite number of steps [8].

In this algorithm, the main problem is to find an acceptable α such that α belongs to the set

$$T(\mu) \equiv \begin{Bmatrix} \alpha > 0 : \phi(\alpha) \le \phi(0) + \alpha\mu\phi^{'}(0), \\ |\phi^{'}(\alpha)| \le \mu|\phi^{'}(0)| \end{Bmatrix}$$

By phrasing the algorithm in terms of $T(\mu)$, we make it clear that the parameter η is independent of the algorithm and only used for the termination. An auxiliary function ψ is also defined:

$$\psi(\alpha) \equiv \phi(\alpha) - \phi(0) - \mu\phi'(0)\alpha$$

Then given α_0 in $[\alpha_{\min}, \alpha_{\max}]$, the search algorithm generates a sequence of nested intervals $\{I_k\}$ and a sequence of iterates $\alpha_k \in I_k \cap [\alpha_{\min,} \alpha_{\max}]$ according to the following procedure:

Set $I_0 = [0, \infty]$

For $k = 0,1,...$

- Safeguarded $\alpha_k \in I_k \cap [\alpha_{\min,} \alpha_{\max}]$ is chosen. Term *safeguarded* α_k refers to the rules that force convergence of the algorithm
- Test for convergence

  i. Terminates if length of I_k is small enough

  ii. Terminates at $\alpha_{\max}$ if $\psi(\alpha_{\max}) \leq 0$ and $\psi'(\alpha_{\max}) < 0$

  iii. Terminates at $\alpha_{\min}$ if $\psi(\alpha_{\min}) > 0$ or $\psi'(\alpha_{\min}) \geq 0$
- Update the interval I_k

  Given a trial value α_t in I with endpoints α_l and α_u, the endpoints α_l^+ and α_u^+ of the updated interval I_+ are determined as follows:

  Case U1: If $\psi(\alpha_t) > \psi(\alpha_l)$, then $\alpha_l^+ = \alpha_l$ and $\alpha_u^+ = \alpha_t$

  Case U2: If $\psi(\alpha_t) \leq \psi(\alpha_l)$ and $\psi'(\alpha_t)(\alpha_t - \alpha_l) > 0$, then $\alpha_l^+ = \alpha_t$ and $\alpha_u^+ = \alpha_u$

  Case U3: If $\psi(\alpha_t) \leq \psi(\alpha_l)$ and $\psi'(\alpha_t)(\alpha_t - \alpha_l) < 0$, then $\alpha_l^+ = \alpha_t$ and $\alpha_u^+ = \alpha_t$
- Trial value determination and safeguarding rules

Rule 1: If $\psi(\alpha_t) \leq 0$ and $\psi^{'}(\alpha_t) < 0$, then $\alpha_t^+ \in [\min\{\delta_{\max}\alpha_t, \alpha_{\max}\}, \alpha_{\max}]$ for some factor $\delta_{\max} > 1$

Rule 2: If $\psi(\alpha_t) > 0$ and $\psi^{'}(\alpha_t) \geq 0$, then $\alpha_t^+ \in [\max\{\delta_{\min}\alpha_t, \alpha_{\min}\}, \alpha_{\min}]$ for some factor $\delta_{\min} < 1$

Rule 3: If the length of I does not decrease by a factor of $\delta < 1$ after two trials, then a bisection step is used for the next trial.

Through these rules we can guarantee that the choice of α_t will force the length of interval to zero and line search will converge eventually.

In addition, some derivative-free line search methods are implemented in certain optimizations such as Fibonacci search, Golden Section search [9] and downhill simplex method [10]. However, there is always a trade-off between looking for the best line-search step and the optimization algorithm itself. These methods will need much more iterations in looking for the best line search step, which is unaffordable in this time-consuming optimization process.

One promising method is multidirectional search algorithm [11]. Since it does not require, or even directly estimate gradient information, complicated and expensive calculations for derivatives are bypassed. Furthermore, it is not uncommon that finite-difference approximations to the gradient may prove unreliable or inaccessible in some cases. The basic idea of multi-directional search is to explore each direction in a linearly independent set of n search directions. With three possible trial steps: the rotation step, the expansion step and the contraction step, optimal solution is approached after some iteration. However, it will take some effort to choose the initial direction and also, improper settings of weight matrix will lead to divergence in few steps.

3.5. Practice in Multi-objective (MO) Programming

Multi-objective programming is concerned with decision-making problems in which there are several conflicting objectives. That is, for many such problems, the decision-maker wants to attain more than one objective in selecting the action while satisfying various constraints. Another characteristic of these problems is that the objectives are apparently noncommensurable. As a matter of fact, any intermediate results are not unique, but provide an infinite set of optimal solutions: the Pareto set [12].

Mathematically, these problems can be represented as:

$$\min\,[\,f_1(x),\, f_2(x),\ldots,\, f_k(x)]$$

where $x \in R^n$ is an decision variable vector. Any or all of the functions may be nonlinear. In literature, this problem is often referred to as a vector minimum problem (VMP). Respectively, the decision vector x^* is a Pareto optimal solution if there does not exist another decision vector x such that $f_i(x) \leq f_i(x^*)$ $i = 1,\ldots k$ with at least one strict inequality.

Typically, to solve a MO problem, it is necessary to follow these steps [13]: a) Define the useful objectives; b) Find the Pareto set; c) Choose a solution from Pareto set. Step c) is the most important, because the final solution depends on the point of view of the decision maker, who has to take into account the relative importance of the conflicting objectives.

Traditionally, there are two approaches to determine the Pareto set. One of them is to optimize one of the objectives while appending the other objectives to a constraint set so that the optimal solution would satisfy these objectives at least up to a predetermined level. The problem is given as:

$$\begin{aligned} &\min f_i(x) \\ &s.t. f_l(x) \le a_l, l = 1,\ldots k \setminus i \end{aligned} \tag{3.12}$$

where a_l is any acceptable predetermined level for objective l. The other approach is to optimize a super-objective function created by multiplying each objective function with a suitable weigh and then by adding them together.

$$\min \sum_{i=1}^{k} w_i f_i(x) \tag{3.13}$$

The weights are usually normalized so that $\sum_{i=1}^{k} w_i = 1$ and various weights reflect the preference of the decision-maker to the vector.

Both of the above approaches are ad hoc at best. Often they lead to a solution which may not be the best or most satisfactory. Because of the conflicting nature of the multiple criteria, the problem becomes complex and difficult to choose the acceptable levels a_l's in (3.12) or weights w_i in (3.13).

4. Transient Stability

4.1. Methodology

In this part, the transient stability constraints related to transmission line transfer capability are investigated. The calculation and further analysis are based on two practical cases, 1997 summer peak case and 1998 spring peak case of WSCC. Due to the difficulties in estimating the transient stability limit for such a large-scale power system, transient simulations are carried out for specific contingencies, such as the simultaneous outage of two Palo Verde nuclear generators, which was in fact the limiting contingency for the two cases. In this way, we are able to indicate the interactions between the transient stability constraint and interarea tie-line flows. In particular, we will study how and to what extent the COI capability is affected by different flows from NW (Northwest) to its neighboring power grid, such as BC (British Columbia) and ID (Idaho).

4.2. Case Study

Batch programs were developed for automatically computing the COI transfer capability for transient stability constrained cases by repeated runs of EPRI transient stability program ETMSP and BPA power-flow program “pf”. The program first modifies COI flow by running “pf”, then runs ETMSP for contingencies and finally analyzes the output to check for transient stability.

Using the batch programs, we carried out preliminary analysis of the effects of different path-flow levels on COI capability for a 1997 summer peak case, which had a low COI capability of 4175 MW, and a 1998 summer peak case, which had a critical COI capability of 4700 MW. In both cases, COI capability was limited by transient stability of the double Palo Verde outage contingency (PV2). For the PV2 contingency, COI margins are calculated under different BC-NW flows. Simulation results in 1998 Spring and 1997 Summer show that decreasing the BC to NW path flow is helpful for transient stability, and thus for improving COI capability. Similarly, increasing ID to NW path flows is helpful for increasing COI capability.

For 1998 Spring case, COI critical MW limit is 4700 MW for the base case BC to NW flow of 1267MW, and the system is transient unstable for PV2 when COI flow >= 4700 MW. Between COI flows at 4625 MW and 4700MW, the system is transient stable for PV2 but Malin voltage goes less than 400 kV during the transient and the transient voltage constraints may also apply.

The following table summarizes the effect of transient stability COI MW limit under different BC-NW flows.

Table 4.1. 1998 Spring peak case results.
Base case: BC-NW=1267 MW.
COI MW limit=4700 MW (transient stability).

MW change in BC to NW flow (MW)	MW change in COI limit (MW)
+100	-25
-250	0
-330	0
-450	+200

Table 4.1 shows that decreasing the BC to NW flow by 450 MW can improve COI transient stability margin by 200 MW.

For the 1997 Summer case, for the base case BC to NW flow of 2204MW, the COI critical limit is 4175 MW. In our studies, we see that if BC to NW flow is decreased by more than 100 MW, COI margin would increase.

Table 4.2. 1997 Summer peak case
Base case: BC to NW flow = 2204 MW.
COI limit = 4175 MW (transient stability).

MW change in BC to NW flow (MW)	MW change in COI limit (MW)
+30	-25
-30	0
-50	0
-100	+25
-150	+50
-200	+50
-250	+75

Briefly, this report shows that the COI transfer capability when limited by transient stability is sensitive to the BC to NW transfer path flows.

Similarly for the 1997 summer peak, the following table shows the effect of ID to NW flow on the COI capability.

Table 4.3. 1997 Summer peak case study summary

MW change in ID to NW flow (MW)	MW change in COI limit (MW)
+180	+75
-30	-25

Roughly, the higher the Idaho to Northwest path flows, the better the PV2 transient stability for improving the COI capability. These studies need to be carried out for other transfer paths and for other seasonal cases so that we can develop global strategies for improving COI capability limits. Moreover, the recent WSCC seasonal cases have been constrained by reactive power-flow constraints. The preliminary studies in this section show that both the transfer path-flows from BC to NW and from ID to NW can have significant impact on COI capability, when it is limited by PV2 transient stability constraint.

Owing to the extremely time-consuming nature of transient stability simulations, optimization algorithms were not implemented for addressing the transient stability constraints. Instead, we approach the problem for small-signal stability constraints in Chapter 6.

5. Voltage Security

5.1. Methodology

As far as voltage security is concerned, we can usually determine its security level by obtaining the reactive power margins at certain critical buses. From previous experience in WSCC planning studies, when COI capability is limited by voltage security, we can focus on the reactive power margin (QV margin) at Malin bus (which is on the COI tie-lines and is located near the California-Oregon border) to study how COI capability is influenced by other transfer path flows and how it is maximized to gain projected benefit in the deregulated environment.

This problem is solved by BFGS method, a typical quasi-Newton nonlinear programming methods mentioned in Chapter 3. Our objective is to maximize the QV margin at Malin bus and the control variables are set as the power generation from areas adjacent to NW. For simplicity in the application of the BPA power-flow program *pf*, we only reschedule the real power output from the slack bus of different areas so that the respective tie line flows are changed as a consequence. An alternative way is to redispatch the power among some generators with large capacity. A simple comparison will prove their equivalence later.

On the other hand, considering that the total generation in the system should remain balanced with the total loads under any circumstance, we set the power generation from NW as a dependent variable. Consequentially, the COI flow is also kept constant, since the generations at the other end of COI, PG&E or Southern California (SOCALIF), do not change at all. In the final optimal solution, the voltage security level, i.e., the QV margin should be enhanced both in the base case and for specific contingency cases.

In the context of power system operation and power markets, our interest is focused on how much MW benefit can be expected on the COI transfer capacity after operators redispatch the generation as suggested by the optimization process. Our procedure is as follows:

- Starting from the previous optimal solution, change the generation from PG&E and NW with the same amount so that COI flow is increased gradually.
- Assuming the transfer capacity was limited by voltage security, the QV margin before the redispatching denotes the critical value for security. Check the QV margin with increased COI flows until it matches the voltage security level before the optimization.

The difference in COI flow is the projected benefit from the optimization procedure. With this new set of solutions, QV margin is almost the same as with the original set of path flows. However, more power is transmitted over COI by redispatching of neighboring path-flows while meeting the same voltage security requirements. Hence, more benefit could be obtained without endangering the system voltage security.

Similar to the previous research on transient stability constraints, batch programs are developed in the implementation as well. BPA *pf* power-flow software engine acts as main tool for obtaining the QV margin during each iteration and for gradient calculation. There is a lot of coding work in file manipulation, such as reading the result file (with the file name extension *pfo* or *QVPT*) and in locating the specific generations precisely at the proper position in the data-input file (with the file name extension *NET* or *PFC*).

5.2. Case Study

5.2.1. Base case

By taking 1998 Spring peak case as our computational base case and by adjusting slack bus generations to improve the objective, we can maximize the QV margin by +144 MVAR.

Table 5.1. Base Case (1998 Spring Peak)
Control variables: Area Power Generations

Area	BC	ID	MT	WK	NW
Slack Bus Name	GMS 6-8	Brownlee	Kerr	Waneta A	Coulee 2
Slack Bus Generation (MW)	678.7	295.4	110	165.8	2055.5
Area Power Generation (MW)	1700	399	595	70.2	6520
QV Margin (MVAR)	1944.06 (V=0.90)				
Scheduled Area Power after Optimization (MW)	1742.98 **(+42.98)**	863.58 **(+341.8)**	830.30 **(+235.3)**	160.20 **(+90)**	5687.1 **(-832.9)**
QV Margin (MVAR) (After Optimization)	2088.38 (V=0.90) (+144.32)				

Table 5.1 also implies that Idaho and Montana should provide more power to improve the voltage security situation for the base case power-flow scenario.

Alternatively, we can also redispatch some specific generators located in various regions to maximize the QV margin. Seven generators in BC, ID and MT other than slack buses are thus rescheduled and two other large capacity generators in NW are operated subject to the entire energy difference in the system (Table 5.2).

Table 5.2. Base Case (1998 Spring Peak)
Control variables: Generators other than slack buses

Generator Name	**Region**	**Original Generation**	**Rescheduled Generation**		**Generator Name**	**Region**	**Original Generation**	**Rescheduled Generation**
KEMAND	BC	746.3	755.7		CHELLSC	ID	200	615
CANYON	BC	554.0	560.1		BRIDGER	ID	530	633
REVELSTK	BC	1350	1381		JOHNDAY	NW	2325	1642
SEVENMI	BC	500	528		MCNARY	NW	900	672
COLSTP	MT	700	988					
QV margin (Original)		1944.06 MVAR			QVmargin(Rescheduled)		2115.93 MVAR	

Comparing Table 5.2 with Table 5.1, the difference in the QV margin after the optimization is about 30 MVAR due to the power-flow redistribution. However, the power generation from individual regions such as BC, ID and MT do not differ too much with the previous aggregate solution. Therefore, to simplify our program and to accelerate the optimization process, it is feasible and reasonable to utilize only the slack bus generations to reach the objective without loss of generality.

5.2.2. Contingency cases

Three contingencies are considered as follows (Table 5.3, Table 5.4 and Table 5.5).

For the critical double Palo Verde contingency, Table 5.3 shows that significant improvement in the security margin results from reasonable redispatching of the three path flows from BC, ID and Montana to NW. Later in section 5.2.3, we will compute the actual improvement in COI MW capability from the increased voltage security benefits.

Table 5.3. Contingency Case I
Double Palo-Verde generator outage

Area	BC	ID	MT	WK	NW
Area Power Generation(MW)	1700	399	595	70.2	6520
QV Margin (MVAR)	523.52(V=0.96)				
Scheduled Area Power after Optimization(MW)	1547.7 **(-152.3)**	596.8 **(+197.8)**	584.0 **(-9)**	-207.6 **(-277.8)**	6763.3 **(+243.2)**
QV Margin (MVAR) (After Optimization)	674.15(V=0.96) **(+140.63**)				

On the other hand, for the double Diablo generator outage contingency in Table 5.4, large redispatch of path-flows is necessary for impacting on COI transfer capability.

Table 5.4. Contingency Case II
Double Diablo generator outage

Area	BC	ID	MT	WK	NW
Area Power Generation (MW)	1700	399	595	70.2	6520
QV Margin (MVAR)	906.14(V=0.96)				
Scheduled Area Power (MW) After Optimization	1757.94 **(+57.96)**	773.66 **(+374.7)**	859.77 **(+264.77)**	336.68 **(+266.48)**	5556.15 **(-963.85)**
QV Margin (MVAR) (After Optimization)	1133.83(V=0.96) (+**227.69**)				

Table 5.5. Contingency Case III
Single COI transmission line (Olinda-Captain Jack) outage

Area	BC	ID	MT	WK	NW
Area Power Generation (MW)	1700	399	595	70.2	6520
QV Margin (MVAR)	1200.63(V=0.89)				
Scheduled Area Power (MW) After Optimization	1736.39 **(+36.39)**	732.41 **(+333.41)**	865.25 **(270.25)**	233.82 **(+163.62)**	5716.33 **(-803.67)**
QV Margin (MVAR) After Optimization	1318.24(V=0.89) (+**117.61**)				

It is apparent that QV margin could be increased by more than 100 MVAR after the regional energy generation is rescheduled. Although the increment is only a small proportion of the total QV margin, it is of great importance to enhance the system voltage security under such serious contingency situations. Hence, our optimization algorithm has proved to be successful and the efficiency is verified.

We also recognize that different tie-line flows (or regional energy generations) will impose different effects on power system performance. For example, the importance of Idaho is observed since it contributes the most among all the control areas, both in the base case and in contingency cases, while the activity in B.C.Hydro is not that significant to improve the entire system performance.

5.2.3. Projected MW benefits

The rescheduled generation and transmission plans are illustrated with Northwest topology graphs in Fig. 5.1 and Fig. 5.2. The green color indicates the generation is increased and the gray color means the generation is decreased to improve the Q margin level. Such methodology provides us the possibility to obtain benefits from coordinating the generation and transmission in various regions.

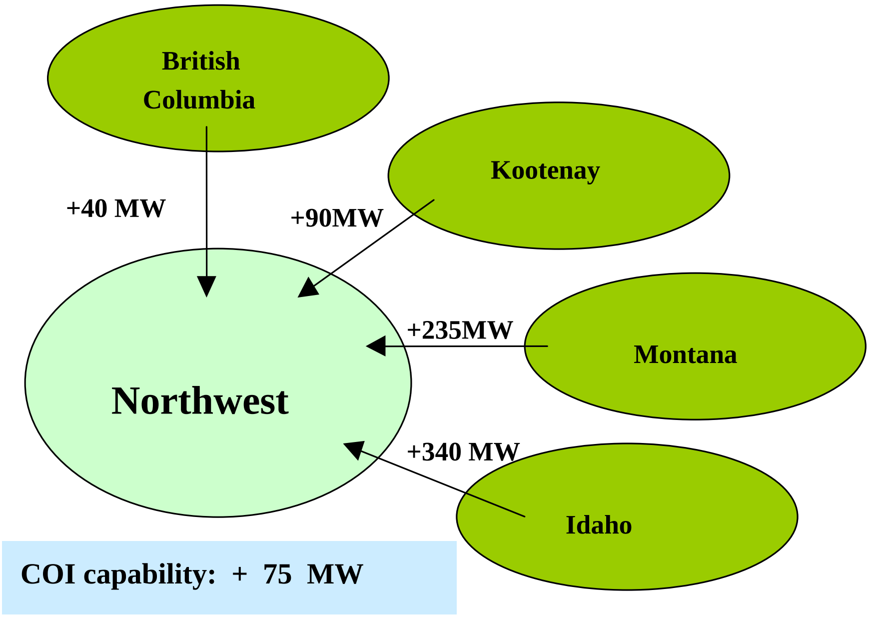

Fig.5.1. Rescheduled power generations and projected MW benefit (Base case)

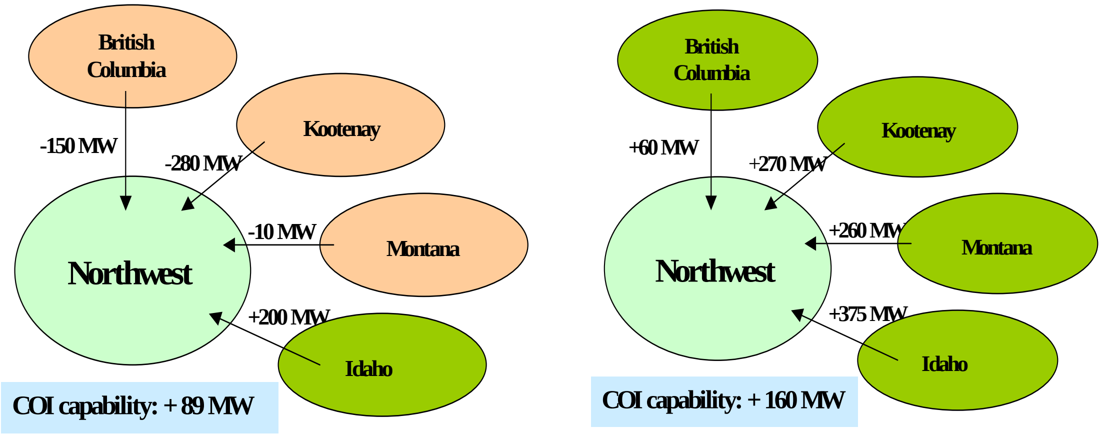

Fig.5.2 Rescheduled power generations and projected MW benefits
Left: Double Palo Verde outage. Right: Double Diablo Canyon outage

Based on the methodology proposed in Part 5.1, projected benefit from the energy redispatch is tabulated (Table 5.6). Furthermore, special contingency situation during generator maintenance is explored.

Table 5.6. Projected COI capability MW Benefits

Case Number		Orig. QV (MVAR)	Optimized QV(MVAR)	Benefit (MW)	Case Number		Orig. QV (MVAR)	Optimized QV(MVAR)	Benefit (MW)
1	PV2	523	674	+89	5	PV2	396	533	+80
	D2	906	1133	+160		D2	669	770	+45
2	PV2	440	556	+50	6	PV2	329	487	+80
	D2	793	909	+118		D2	710	808	+80
3	PV2	477	575	+50	7	PV2	277	629	+240
	D2	768	972	+151		D2	628	844	+110
4	PV2	592	764	+119	8	PV2	263	474	+144
	D2	904	1023	+84		D2	641	706	+50

PV2: Double Palo-Verde Outage Contingency D2: Double Diablo Outage Contingency

Case 1: Base case

Case 2: McNary generator out of service.

Case 3: Lower Monumental (Low Mon) generator out of service.

Case 4: Chief Joseph generator out of service.

Case 5: John Day generator out of service and the real power deficiency is compensated from generators nearby, Low Mon, Low Granite, McNary and Chief-Joseph.

Case 6: Hanford-Coulee 500KV transmission line out of service.

Case 7: Ashe-Low Mon 500KV transmission line out of service.

Case 8: McNary-Sacjwa_T 500KV transmission line out of service.

From the results above, it is clear that the most serious contingency occurs around area centering Hanford, either transmission line tripping out or generator out of service. Such observation is consistent with the report of BPA [14]. However, by taking advantage of interarea tie line flow coordination, the potential danger to the system security can be reduced significantly.

In addition, the utility owners want to maximize their revenue without restricting reliability or security. By coordinating transmission line transfer capability under voltage security constraints, our attempts make it possible to satisfy their demand. In Table 5.6, the COI MW benefit varies from +45 to +240 MVAR. Given that this path is economically one of the most expensive paths in the western system, the path owners can choose some strategies to gain transmission profits and at the same time, the security level can be maintained or enhanced.

6. Small-signal Stability

6.1. Methodology

In large power systems, small-signal stability problems may either local or global in nature [15]. Local problems are usually associated with rotor angle oscillations of a single generator against other generators in the system, or oscillations between the rotors of a few generators close to each other. By contrast, global problems are caused by interactions among large groups of generators and involve oscillations of a group of generators in one area swinging against another group. Such oscillations are called *interarea mode oscillations*, which will affect the stability and security of the power system significantly.

We concentrate our research interest on the 0.25-0.3 Hz mode interarea oscillations, because in WSCC cases, low frequency oscillations in this range involves a large amount of generators and weakens the steady stability greatly. For instance, the small-signal instability of the 0.25 Hz COI mode led to the August 10, 1996 western area black-out. It is clear that damping levels of the interarea modes can restrict the ability to transfer more power over certain transmission lines.

Similar to the methodology in dealing with voltage security constraints, we will apply BFGS algorithms to maximize the damping ratio of the 0.25 Hz interarea mode in WSCC cases. The slack bus generations in ID, BC, MT and WK are selected as control variables, while generations from NW are taken as dependent variables to keep the COI flow unchanged. Later, we will take advantage of our optimization result to compute COI MW benefits like before.

6.2. Implementation

PEALS, which is developed by EPRI, is a powerful software package for computing specific eigenvalues of large-scale systems for carrying out fast small-signal stability analysis. Therefore, to investigate the sensitivity of control variables to the objective, we applied PEALS to facilitate our computation at first.

It is well-known that typically for WSCC planning cases, the damping of the 0.25 Hz mode decreases monotonically with increase in COI transfer levels. In the first study, we alter the COI transfer by 20MW or 50MW to see what will occur on the damping ratio as computed by the PEALS program.

From Table 6.1, we notice that the damping ratio of the 0.25 Hz mode changes with respect to even little disturbances in the control variables. In addition, it is notable that such changes are abnormal and the relationship between them is not monotonous. Since the gradient computation is based on central differentiation, the strong nonlinearity will cause such gradient-based optimization algorithm as BFGS method invalid. Hence, the convergence cannot be guaranteed with inaccurate gradient computation.

Table 6.1 Sensitivity analysis with PEALS

BC		ID		MT		WK	
Output	Damping	Output	Damping	Output	Damping	Output	Damping
1600	.0362	399	.0565	595	.0565	-109.8	.0070
1650	.1037	419	.0485	615	.0359	-89.8	.0489
1700	.0565	439	.0293	635	.0367	-69.8	.0332
1750	.0176	459	.0782	655	.0195	-29.8	.0406
1800	.0504	479	.0405	675	.0275	10.2	.0340
1850	.0468	499	.0664	695	.0252	50.2	.0475
1900	.0524	519	.0777	715	.0354	70.2	.0565

Based on Table 6.1, we observe that the program PEALS is not sufficiently accurate in estimating the damping values of the 0.25 Hz mode in large WSCC cases, an alternative way is derived as below based on PRONY damping estimation of transient stability simulations:

1) Compute the base case power flow with BPA-pf.
2) Using BSE file from 1), carry out a 10 second transient simulation under a small disturbance with the EPRI transient stability program ETMSP.
3) Read BIN file from 2) with EPRI program OAP, and use the data from channels related to COI MW flow for computing the interarea mode damping value.

In step 3, Prony algorithm is applied in OAP to complete the spectrum analysis and thus the 0.25Hz interarea mode can be distinguished. During the entire procedure, three software packages are utilized in order. Owing to the considerably heavy computation in doing the time domain simulation with ETMSP, this procedure is extremely time-consuming to estimate the damping levels. However, this method proved to be reasonably accurate. Also, since the method purely based on transient stability type simulation is of general interest to any power utility, there is no doubt that its application could be extended further.

In Table 6.2, we compared the damping calculation results with respect to COI flow. Usually, the critical interarea mode will demonstrate less damping when the COI flow grows. With PEALS, the outcome is still meaningless. On contrary, with Prony algorithm in OAP, the damping ratio changes almost monotonously and displays orderliness.

Table 6.2 Comparison of Damping Ratio Calculations
for COI flow variations

COI Flow (MW)	PEALS		PRONY algorithm in OAP	
	Frequency (Hz)	Damping Ratio	Frequency (Hz)	Damping Ratio
4525	.2741	.0615	.3487	.1247
4550	.2722	.0693	.3655	.1108
4575	.2741	.0523	.2918	.1086
4600	.2717	.0621	.2158	.0714
4625	.2704	.0639	.2977	.0932
4650	.2710	.0518	.3748	.1221
4675	.2682	.0653	.2306	.0687

6.3. Case study

Now we can continue our study with the BFGS method.

Transmission Line ASHE-HANFORD is tripped and is reclosed after a short duration for simulating a small disturbance. Table 6.3 indicates the sensitivity and helps us to determine the weight matrix in BFGS. Compared with Table 6.1, following data look much better and more orderly. Generation from ID seems to have more effect in improving the damping.

Table 6.3 Sensitivity analysis
with OAP and Prony Algorithm

BC		ID		MT		WK	
Output	Damping	Output	Damping	Output	Damping	Output	Damping
1680	.06867	399	.06835	595	.06835	70.2	.06835
1720	.06858	419	.06870	615	.06844	80.2	.06846
1740	.06847	439	.06937	635	.06846	90.2	.06842
1760	.06836	459	.06960	655	.06852	100.2	.06817
1780	.06799	479	.06982	675	.06857		

Following the preliminary sensitivity analysis, BFGS algorithm is applied to pursue an optimal power dispatching solution in order to maximize the damping ratio of 0.25HZ mode. Table 6.4 lists the optimum after eight iterations.

Table 6.4 Optimal solution for the base case damping improvement

Area	BC	ID	MT	WK	NW
Area Power Generation (MW)	1700	399	595	70.2	6520
Damping Ratio	0.06836				
Scheduled Area Power (MW) After Optimization	1638.59 **(-61.41)**	669.92 **(+270.92)**	611.54 **(+16.54)**	116.20 **(+46)**	6267.94 **(-252.06)**
Damping Ratio After Optimization	0.07324 (+**20%**)				

To be consistent with the regulations of BPA, we carried on another case in which double Palo Verde generation is tripped out with all governors taking action.

Table 6.5 Optimal solution for the double Palo Verde outage

Area	BC	ID	MT	WK	NW
Area Power Generation (MW)	1700	399	595	70.2	5520
Damping Ratio	0.03674				
Scheduled Area Power (MW) After Optimization	1706.86 **(+6.85)**	499.48 **(+100.48)**	622.95 **(+27.95)**	-18.69 **(-88.89)**	5473.60 **(-46.40)**
Damping Ratio After Optimization	0.05061 (+**40%**)				

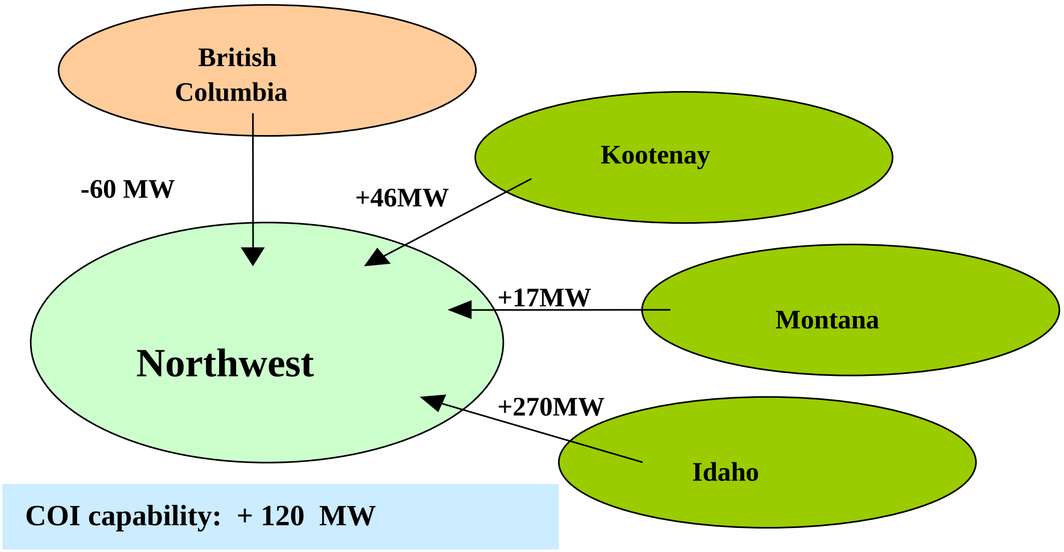

Fig. 6.1. Rescheduled power generations and projected MW benefit (Base case)

With our algorithms, the interarea mode damping could be increased by 20% to 40%. Thus, it is a great progress in improving system performance under small disturbances. Furthermore, if we start similar benefit calculations as Chapter 5, COI transfer capability can be improved by +120 MW for the base case (Fig. 6.1). That is, COI capacity can be increased from 4600 MW to 4720 MW, while the interarea damping is not weakened. Therefore, if some robust and powerful software related to eigenvalue analysis is introduced into our framework, it will make our computation more efficient and much more promising in the current power market.

7. Economic Considerations

7.1. Formulation

One of the main objectives of the modern power industry is to produce and to deliver electrical energy safely and reliably to the end users at low cost. Before the introduction of security and stability concepts to power system operation, the optimal power flow (OPF) problems were usually focused on reducing the economical cost. As the use of networks close to their ultimate ratings led to a fear of line overloading, several security and stability constraints are incorporated into the context of optimal power flow under various considerations of operating constraints [16]. For the same reason, the voltage security and economical cost are combined together in our research project. In other words, we have to solve a typical multi-objective programming problem: the voltage security objective and the economic cost objective.

As a matter of fact, cost can be reduced without endangering voltage security level by choosing different weights on the tie-line $ cost and constraints on voltage security. The choice of weights is totally dependent on the operator's preference and experience. During the optimization process, the COI flow is kept constant and tie-line flow is controlled by slack bus generations in Northwest and its adjacent utilities. Then the problem is formulated as below:

$$\min \; w_1 f_1 + w_2 f_2$$

w_1 and w_2 are weights corresponding to Q margin and cost, while f_1 and f_2 represent the two objectives, respectively. In particular, we set $w_1 + w_2 = 1$. Then, BFGS algorithm is applied to find the optimal value.

7.2. Case study

In Table 7.1, we assume that there exists various transmission costs over different transmission paths. Furthermore, when the direction of power transmission over these paths are reversed, for example, the real power is delivered from BC to NW, the price is set to zero. That is, the power is free of charge if it is sent back to NW grid.

Table 7.1 Cost of transmission paths

Path	NW-BC	NW-ID	NW-MT	NW-WK
Price($/MW)	1.5	2.5	2	1.8

Table 7.2 summarizes the solutions under different weight conditions.

Table 7.2 Solutions for different weights

Area		BC	ID	MT	WK	NW
Area Power Generation (MW)		1700	399	595	70.2	6520
Q Margin (MVAR)		1944		Cost ($)		873
I	Scheduled Area Power (MW)	1369.94 **(-330.06)**	680.17 **(+281.17)**	452.99 **(-142.01)**	-266.02 **(-336.22)**	7047.12 **(+527.12)**
	Q Margin (MVAR)	1990**(+46)**		Cost ($)		365**(-508)**
II	Scheduled Area Power (MW)	1496.18 **(-203.82)**	604.31 **(+205.31)**	540.34 **(-54.66)**	-122.44 **(-192.64)**	6765.81 **(+245.81)**
	Q Margin (MVAR)	2012**(+68)**		Cost ($)		445**(-428)**

Case I: $w_1 = 0.92$, $w_2 = 0.08$

Case II: $w_1 = 0.95$, $w_2 = 0.05$

Compared with Case II, we put more emphasis on economical cost in Case I. Hence it is reasonable that the solution of Case I will lead to lesser cost than that of Case II. Likewise, since the weight corresponding to QV margin in Case II is larger, the optimization result in Case II will have better voltage security performance than that of Case I. It is natural that the final solution indicates the coincidence with our experience and estimation. As for the system operators, they only need to alter the weight vector based on their preferences, a different set of solution will be created. Moreover, some other objectives can be taken into account, such as small-signal stability constraints, etc.

8. Future Studies

1. Multi-objective packages

In the actual operation and dispatching, more than two objectives may be involved. Therefore, there is a great need to develop some more efficient and general software package so that the operators can choose their optimization goal and preferences flexibly. However, most current commercial software in power industry cannot meet the increasing demand of power market. In addition, the objectives may have strong interactions between each other and particularly for large-scale power system, various operation and load conditions make it extremely complicate to continue the optimization process. In some cases, it is almost impossible to determine the objectives quantitatively and precisely. As a result, it will be much more difficult to establish proper weight vector in order to reflect the users' demands.

2. Efficient algorithms

Almost all of our optimizations take advantage of BFGS method with sufficient step size, in which it is inevitable to approximate the gradient vector with central differentiation. Unfortunately, such calculation exhausts a large proportion of the CPU time because of the large size of research system. Moreover, there is an instinct tradeoff between the step search and total number of convergence iterates. If we spend more time in step search for a suitable sufficient step, then it will take much less time in BFGS iterations. And vise versa. Therefore, if some derivative-free nonlinear optimization algorithm can be introduced, the efficiency will be improved and our software package will be more practical for industry applications.

3. Robust eigenvalue software

As we see in Chapter 6, the present version of PEALS is not suited for consistent computation of the damping levels of the eigenvalues in WSCC because of the stressed power-flow conditions and strong nonlinearities in this large system. Therefore, we used a general-purpose but time-consuming way to obtain the mode damping by carrying put PRONY analysis of ETMSP outputs following a small disturbance. We are calling for some more powerful and robust software for eigenvalue computations in large systems so that it can be embedded into our package to reduce the computation time.

4. Economical consideration

In Chapter 7, a simple case study is mentioned as an application with economical considerations. With the further development of deregulations and reorganizations of power market, many new problems will emerge as a result. To avoid the potential energy crisis in the future, new strategies should be designed and adopted incorporating both the economical expense and all other security objectives. In other words, more economical behavior should be taken care of in the context of stability and security.

5. Application of flexible control variables

In Table 5.2, we demonstrated how to maximize the voltage security level via the control of various generators over different power grids. In the other parts of the case studies, for simplicity, we control the tie-line flow in the most direct way, the slack bus generations. In fact, there are numerous strategies in transmission line control, such as FACTS components, capacitor banks, load shedding, etc. To make our software more flexible and practical for the operators, it is necessary to consider all these control operations and corresponding operation limits. Of course, these decisions are made depending on the operators' experience and relevant operations should be complied with power system guidelines.

9. Conclusions

In this project, coordination strategies for transmission line transfer capabilities are proposed and analyzed to address the power grid in a global viewpoint. A practical optimization methodology is thus demonstrated to achieve such objectives. By establishing corresponding research models and by recognizing interactions of different path power flows, the transient stability, voltage security and small-signal stability constraints are studied quantitatively. A detailed nonlinear programming algorithm, BFGS method, is stated and is verified with the actual WSCC system. Further research shows that through coordination of different transmission path inside a large power system, benefits gained from power markets can be improved without sacrificing system stability and security.

The document also indicates that it is very promising to continue the research on the coordination of transfer capability with the consideration of the economical demand of power market. We observe that the improvement of the algorithm and the participation of the multiple constraints will be of vital importance to the power market. In the last part of the document, the existing difficulties and potential feasible solutions of the project are stated.

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