reserve requirements on thermal power systems, within probabilistic production costing models and others based upon load distribution functions. The aim is to show that such models can be developed to approximate the full range of dynamic penalties associated with thermal power system operation.

Part-Loading and Reserve

The efficiency of thermal units is generally reduced when they are part loaded. This may occur for several reasons, and the loss is not usually captured in statistical cost models. By approximating fuel use as a linear function over the operating range, any loss associated with part loading by a total power y is then given by $k^p y$, where k^p is the incremental loss defined by the efficiency line. Analytic expressions for part loading losses can then be obtained for a number of particular cases. If within a group of similar plants, it is operating policy to part load all units in the tranche down to a specified lower limit δ before beginning to take any off the bars, the associated part load loss per unit time is given by:

$$C_j^p = k^p \left[\frac{1-\delta}{\delta} \int_{p_l}^{p_\delta} F_{j-1}(x)\, dx - \int_{p_\delta}^{p_u} F_{j-1}(x)\, dx \right] \tag{1}$$

Here p_l, p_δ, p_u are respectively the lower loading point, the part load point (the effective power level at which all units are at their part load limit) and the upper loading point (with all available units of the tranches at full power). $F_{j-1}(x)$ is the effective load distribution curve (ELDC) obtained before loading the first unit of the jth tranche (for deterministic analysis, the simple LDC may be used, with capacities derated by their forced outage probability).

Often, part loading units is more expensive than offloading them, and is done to maintain adequate short term reserve. If it is necessary to maintain R^s reserve capacity within the jth plant tranche, the cost is given simply by:

$$R^s k^p \{ F_{j-1}(p_{j-1}) - F_j(p_j) \} \tag{2}$$

where p_j is the capacity of units/tranches up to and including the jth. An additional and more complex factor is then required to account for the fact that some units need to be brought on-line before others, loaded earlier in the merit order, are at full power.

Load Prediction Error and Fast Response Plant

In order to estimate the likely requirement for reserve, and the penalties associated with maintaining inadequate reserve, a load error prediction function $\epsilon^t(p)$ can be used. This expresses the RMS error in predicting load p at time t in advance (for analysing spinning reserve issues, t may be taken as the time required for bringing any plant which is held at hot standby on-line, typically 1-2 hours). If the thermal reserve is inadequate to meet the realised load, fast response plant will have to be used. The total out-of-merit energy demanded of the fast response units is then given by:

$$\int_0^{p_s} \epsilon(p) G\{\gamma(p)\} f(p)\, dp \tag{3}$$

where $f(p)$ is the load density function, p_s is the total steam capacity (the loading point above which the fast response plant is in merit), and $\gamma = R^s/\epsilon$, the ratio of scheduled reserve to the standard error. $G(\gamma)$ is Farmer's expression for the utilisation energy, $\int_\gamma^\infty (x - \gamma) Z(x) dx$, where $Z(x)$ is the normalised distribution of the error (most probably, a Normal distribution).

This formulation allows an economically optimal reserve level γ^* to be defined for a given level p, in terms of the incremental part load cost and the difference Δc^v between the variable (fuel) cost of the steam and fast response units:

$$\int_{\gamma^*}^{\infty} Z(x)\, dx = k^p / \Delta c^v \tag{4}$$

Other criteria may dominate the reserve requirement, however.

Finally, and somewhat more speculatively, it is possible to approximate the costs of maintaining adequate "banked" plant to meet longer term errors in load prediction (1-10 hours). With banked reserve capacity $R_m^b(p)$, $m = 1, \cdots M$ at different (increasing) lead times, the following form may be obtained for the costs of maintaining such banked reserve:

$$\text{Banking cost} \sim 1/2 \sum_{m=1}^{M} \int_{p+R_{m-1(f)}}^{p+R^b} c_{b_m(x)}^{b_m(p)}\, dx\, dp \tag{5}$$

where c_m^b is the unit cost associated with the level m, and the factor 1/2 arises from the natural presence of hot plant under conditions of continuously varying load.

Application

To increase the efficiency of the analysis, the various equations can be formulated in terms of cumulants of the load density function, and the uncertainty function can be expressed in cumulant form using the approach developed for the transition frequency function (Part I). This leads to a very efficient formulation; in cumulant form, the complete cost analysis can run up to several hundred times faster than hourly simulation over a full year.

Comparison with outputs from an hourly simulation model under a wide range of different reserve requirements demonstrates close agreement between the models, despite the simplifications involved in the statistical analysis, even under severe conditions.

The approach thus enables a wide range of operational issues to be included in a probabilistic context. Furthermore, the efficiency of the methods makes them appropriate for optimisation studies of plant and/or operational parameters, and for sampling studies performed under a range of fuel cost and other uncertainties.

---

88 SM 729-6
May 1989

Hydrothermal Optimal Power Flow Based on a Combined Linear and Nonlinear Programming Methodology

H. Habibollahzadeh*, G. X. Luo, and A. Semlyen
Department of Electrical Engineering
University of Toronto
Toronto, Ontario, Canada

Computation of active and reactive OPF has received widespread attention in the last decade. It is of current interest to many utilities and has been identified as one of the most important operational needs. Real-time application in particular requires the computer codes to be fast and robust, high accuracy having less importance. In this type of problems the choice of method lies between two main approaches: nonlinear and linear programming techniques.

Nonlinear programming techniques consider accurate active and reactive OPF models, but have several drawbacks, including slow convergence, complexity, and difficulties involved in handling constraints and in adapting to different problems.

The LP method has been reported to be reliable and fast in

* At present with Ontario Hydro

solving linearized OPF models. It is very convenient for handling the constraints. But on the other hand, it produces solutions that are at the corners of the linearized feasible region while the nonlinear objective could lie anywhere within the feasible region. An important drawback is that LP allows only for a linear objective function. Oscillatory behavior may also occur if the LP is iterated without good linearization of the constraints.

The work reported in this paper focuses on the active problem even though it can be applied equally to the reactive power problem. It is based on the combination of the two methods, to take advantage of the strong points in one to compensate for the shortcomings of the other. In the work presented here, Zoutendijk's feasible directions method for solving nonlinear programming problems has been used. In this method an incremental model using the gradient at an existing solution is employed. A small linear domain around this solution is chosen to ensure good linearization. The original constraints that bind in this small region are included in the incremental model. This model is a sparse LP with embedded network structure. Solution of the LP produces a feasible improving direction. The nonlinear objective is then optimized along this feasible direction within the original nonlinear constraints. The process is continued at the new solutions obtained until the problem converges.

Several modifications have been made to avoid the general problems in existing optimization techniques, mentioned earlier. First, to exploit the speed of the LP technique, the first solution is produced using a linear model in which a piecewise linear approximation of the cost curve and linearization of the nonlinear constraints is employed. This will result in a near optimum solution that can be used to start the nonlinear programming technique. Second, a branch oriented formulation of OPF is used as opposed to a nodal one to provide an accurate linearization of the problem. Third, the sparsity and the embedded network structure of the constraints are exploited to speed up the solution technique. Fourth, the method of parallel tangents is used to speed up the convergence of the nonlinear technique. The procedure developed in this work is capable of starting from an infeasible initial solution. Figure 1 demonstrates the flow chart for this technique.

The hydraulic system is not normally included at the instantaneous OPF level. It involves time due to the water energy storage and is normally considered in daily, weekly or seasonal optimizations. Hydraulic modeling in OPF for systems with high share of hydraulic generation is essential. The present work includes the hydraulic system in the OPF.

Test results from the application of the proposed technique are presented to demonstrate the capability of the solution technique. The specific characteristics of the model are:

1) The method is particularly efficient for constrained OPF problems, since it can start with an active set of constraints and add the new binding constraints in a simple manner so that the increase of CPU time is very low.
2) The program can start from an infeasible initial solution.
3) The hydraulic system is taken into account for a power system with considerable amount of hydraulic generation.
4) All components of the power system and their limits can be considered in a very simple formulation.
5) The expanded branch oriented formulation used in this work makes it possible to produce an exact incremental model and consequently very good optimum feasible directions. This renders the solution technique very efficient.

Step One
Power flow solution

↓

Step Two
Feasibility adjustment

↓

Step Three
Optimization with piece-wise linear approximation of production cost curves

↓

Step Four
Optimization with quadratic approximation of production cost curves

Fig. 1. Optimization flow chart.

88 SM 661-1
May 1989

Unit Connected Generator with Diode Valve Rectifier Scheme

S. Hungsasutra and R. M. Mathur, Senior Member, IEEE
Department of Electrical Engineering
Faculty of Engineering Science
The University of Western Ontario
London, Ontario N6A 5B9

The application of diode valve rectifier to unit connected generators feeding hvdc converter has long been mentioned in the past [1] in order to provide a substantial reduction in converter station cost. However, such an arrangement has not been implemented because of some disadvantages related to dc line fault clearing, reversal of power flow, etc. This paper proposes a few types of control and protection schemes for the generators and the dc link to minimize the time required to restore full power following a temporary dc line fault.

Control and Protection Schemes

With the application of diode bridge rectifier, it is essential that the dc voltage at the rectifier must be controlled by the generator excitation. Under dc line fault conditions, the system must be protected either by the use of dc breaker on the dc line, ac breaker between the generator terminals and the converter transformer or by field reversing. Combinations of excitation control employing field reversing together with ac breaker were selected to evaluate the performance of the test system shown in Fig. 1. These combinations were:

a. Excitation controlling ac voltage, and ac circuit breaker.
b. Excitation controlling ac voltage employing field reversing, and ac circuit breaker
c. Excitation controlling dc voltage employing field reversing, and ac circuit breaker
d. Excitation controlling dc voltage without any breaker.