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MULTI-YEAR MULTI-CASE OPTIMAL VAR PLANNING

Ying-Yi Hong, student member — Institute of Electrical Engineering, National Tsing Hua University, Hsinchu, Taiwan, R.O.C.

David I. Sun, member — ESCA Corporation, Bellevue, Washington, U.S.A.

Shin-Yeu Lin — Institute of Control Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.

Chia-Jen Lin, senior member — Taiwan Power Company, Taipei, Taiwan, R.O.C.

ABSTRACT

This paper presents an integrated methodology for long term var planning. The timing (year), the location and the amount of var compensation would be determined. The system security and investment and operating economics are also taken into account. The proposed methodology is an integration of the Newton-OPF with the Generalized Benders Decomposition (GBD).

The total problem is decomposed into two levels: master and slave. The master level deals with the investment decision of installing discretized new var devices. The slave level deals with operating the existing controllers, in conjunction with the new devices solved in the master level, to maintain system feasibility and to reduce MW losses.

The overall solution methodology contains numerous extensions to the basic theory. Tests performed on actual Taiwan Power system data have been encouraging. Sample results are presented.

I. INTRODUCTION

The problem of long term var planning deals with the question of when, where and how much var compensation to install in a power system. It is a difficult problem that must consider many complicated security and economic factors, including:

(a) Keep voltage and var within physical and operating limits for the entire system, under any normal and contingent operating conditions.

(b) Coordinate the expansion from the base year towards the horizon year, recognizing expected changes in load, generation, and the network.

(c) Discretize the number of capacitor and reactor banks.

(d) Consider the interaction between existing controllers and the new controllers.

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Conventionally, var planning problem has been handled by a trial-and-error approach utilizing a powerflow program. Early work [1] on optimal var planning focused on introducing optimization technology. The scope of the problem was limited to analyzing single intact system. More generalized model was later presented in [2]. A major advance in optimal var planning was reported in [3], which satisfied system security requirements for both base case and contingency operations, and solution variables for compensation were discretized. Alternative methods of optimization had also been proposed [4,5,6]. While there may be special conditions that these methods would be suitable for, they would generally suffer from unreliable or slow convergence. For problems having non-separable cost functions, most methods would likely to optimize to path-dependent final solutions. Instead of optimizing var planning as one problem, [7,8,9] suggested using Benders Decomposition to split the unwieldy total problem into more manageable partitions. Each partition could then be solved by using a suitable method.

In our investigation, we have applied the Newton-OPF [11,12], rather than the Augmented Lagrange method [7,8,9], in association with the GBD, to solve the long term var planning problem. Important features of the Newton-Benders approach are summarized below:

(1) Use MW loss as slave level objective function. This reduces the difficulty of non-unique slave level solutions that would be caused by a strictly feasibility-oriented slave level objective function, which was used in [9]. The Lagrange multipliers obtained from the slave level solution could be scaled appropriately to generate Benders cuts for the master problem.

(2) Make use of the infeasibility criterion in [10] to generate Benders cut efficiently. By including violation residuals in the infeasible Benders cut, we were able to accept infeasible subproblem solutions with relatively large convergence tolerance. This is particularly important since the subproblem is often border-line infeasible in the Benders iteration.

(3) Use the concept of constraint deadband, instead of heuristic violation weighting factors, to guide system feasibility. In conjunction with (2) from above, this removes convergence problems caused by improper weighting factors.

(4) Embed an effective discretization scheme within the Benders master problem solution process to satisfy integer constraints for capacitor and reactor banks.

(5) Support the use of different cost factors for installing compensators in different years. This cost model for the master problem leads to determining optimal annual var installation over a multi-year planning period.

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At this time, the Newton-Benders method has been implemented to solve the long term var planning problem. In the following section, we will present the mathematical formulation for the multi-case, multi-year and integer constrained problem.

II. PROBLEM FORMULATION

The basic notations are defined as:

N : number of years , n= 1,..., N;

M_n : number of cases for year n, $m = 1, \ldots, M_n$;

J_n : number of candidate buses for year n, $j = 1, \ldots, J_n$;

U_n : new var installation vector including capacitor and inductor for year n;

U_n' : total new var installation vetor from the year 1 to the year n;

U_{jn}^c , U_{jn}^l : new capacitor, inductor installation for bus j, year n;

X_{nm} : solution vector excluding U_n for year n, case m;

$h_{nm}(X_{nm})$: security constraint vector for year n, case m;

Q_{jnm} : var injection for bus j, year n, case m;

QMX_j^c, QMX_j^l : permissible maximum capacitor/inductor installation for bus j;

QMN_j^c, QMN_j^l : original capacitor/inductor installation for bus j;

$g_{nm}(X_{nm},U_n')$: powerflow equations for year n, case m;

$FO_{nm}(X_{nm})$: operating cost at year n, case m (capitalized MW losses);

$FI_n(U_n)$: var investment cost for year n.

and, superscores (underscores) are maximum (minimum) limits. X_{nm} contains the following types of variables:

- voltage magnitude at load bus;
- var generation at voltage-controlled generator;
- bus voltage phase angle;
- MW injection at the slack bus;
- generator voltage regulation;
- transformer tap;
- controllable var injection.

With the above definition, the long term var planning problem could be formulated as follows:

$$\text{Min} \quad \sum_{n=1}^{N} \sum_{m=1}^{M_n} FO_{nm}(X_{nm}) + \sum_{n=1}^{N} FI_n(U_n) \tag{1}$$

subject to

$$g_{nm}(X_{nm}, U_n') = 0 \tag{2}$$

$$\underline{h}_{nm} \le h_{nm}(X_{nm}) \le \overline{h}_{nm} \tag{3}$$

$$\underline{X}_{nm} \le X_{nm} \le \overline{X}_{nm} \tag{4}$$

$$n = 1, \ldots, N. \quad m = 1, \ldots, M_n.$$

$$0 \le \sum_{i=1}^{n} U_{ji}^l \le \sum_{i=1}^{n+1} U_{ji}^l \le (QMX_j^l - QMN_j^l) \tag{5}$$

$$0 \le \sum_{i=1}^{n} U_{ji}^c \le \sum_{i=1}^{n+1} U_{ji}^c \le (QMX_j^c - QMN_j^c) \tag{6}$$

$$n + 1 \le N. \quad j = 1, \ldots, J_n.$$

where U_{ji}^l and U_{ji}^c are discreted variables. Especially,

$$-QMX_j^l \le - \sum_{i=1}^{n} U_{ji}^l - QMN_j^l \le Q_{jnm} \le \sum_{i=1}^{n} U_{ji}^c + QMN_j^c \le QMX_j^c \tag{7}$$

III. METHODOLOGY OVERVIEW

DECOMPOSITION

The long term var planning problem as formulated above could be very large, and has integer constraints for var compensation variable. A way to make it more tractable is to decompose the complete problem into more manageable parts.

Variables in the problem are coupled to each other in two levels. At one level, which we refer to as the 'slave level', variables are coupled through the physical network relationships. They correspond to, for example, the set of variables in a powerflow solution. For each case-index m and year-index n, this form of coupling is defined by (2), (3), (4) and (7). Then at the other level, which we refer to as the 'master level', there is coupling of the variables across different cases and years. This form of coupling is defined by (5) and (6). It involves variables corresponding to additional var compensation in each year. The amount of var added in a particular year affects the total available var injection for different cases in that year, and in all subsequent years. This phenomenon is indicated in (7).

In a study that analyzes M_n cases per year over N years, there are $(M_1+M_2+\ldots+M_N)$ sets of variables. If the variables involved in the master level coupling are held constants in the slave level, then we would have $(M_1+M_2+\ldots+M_N)$ independently-solvable subproblems contained in the slave level. The variables that are held constant for the slave level subproblems would be solved in the separate master problem. The relationship between the master and the subproblems is shown in Figure 1.

Generalized Benders Decomposition theory describes how to coordinate solutions between the slave level subproblems and the master level problem, so that the solution obtained with the decomposed approach would be the same as that from the un-decomposed (integrated) approach.

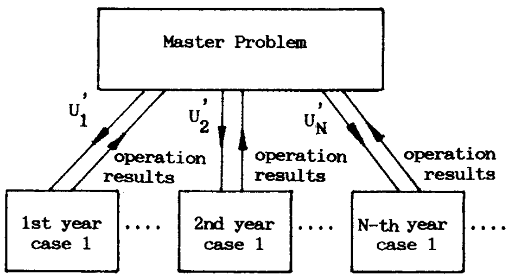


Figure 1. Schematic Diagram of Two levels Approach for Multiple Years, Multiple Cases Var Planning.

Proper convergence with the GBD theory can be assured if the var planning subproblem is convex. While the subproblem may be non-convex, in practice, this has not caused any significant difficulty. Tests performed on different systems, using different execution control parameters, with and without decomposition, are able to converge to consistent optimal solutions. Representative test results are shown later.

SUBPROBLEMS FORMULATION

The amount of var installation determined in the master problem is fixed to be the limits on bus var injection as (7). Hence, the slave level may be decomposed into $(M_1+M_2+\ldots+M_N)$ independent subproblems. Controllable devices would be optimized to achieve operating security and economy for a given network in a given year. Mathematical formulation for the each subproblem is presented below.

$$\text{Min } FO_{nm}(X_{nm}) + FI_n(U_n^*)$$

$$\text{s.t } G_{nm}(X_{nm}, U_n^{'*}) \le 0; \qquad n = 1, \ldots, N; \quad m = 1, \ldots, M_n. \tag{8}$$

where G_{nm} includes power flow equations and other inequality constraints as shown in (2), (3), (4) and (7). The '*' in U_n and U_n' signifies that these are constants in the slave level problem.

SUBPROBLEMS SOLUTION

As far as the GBD theory is concerned, the solution method for the subproblem and the master problem could be chosen independently to best suit their respective characteristics. In our case, we choose to optimize the subproblem by the Newton method. The choice is based on its general strength in solving OPF problems that have non-separable objective functions and large number of inequality constraints. In addition, the Newton method has the following features that make it ideal for solving Benders subproblems:

- it directly solves not only the primal variables but also the dual variables, which are needed to build the Benders cuts.

- it effectively handles infeasible solution which may occur frequently in the Benders Decomposition method.

Since changes to the master problem solution are presented to the subproblems as new limits on var injection at the candidate buses, the optimal solution obtained in the present master-slave iteration for a subproblem serves well as the starting point for that subproblem in the next master-slave iteration. Good starting solution can significantly speed up subproblem convergence. The starting solutions should include all primal and dual variable values as well as the set of active inequality constraints.

MASTER PROBLEM FORMULATION

The master problem optimizes var compensation while observing direct constraints on var installation at each candidate bus, and indirect constraints that reflect slave-level solution characteristics (optimality and feasibility) in the form of Benders cuts. The mathematical formulation of the master problem is presented below.

$$\text{Min } Z$$

$$\text{s.t } Z \ge \sum_{n=1}^{N} \sum_{m=1}^{M_n} FO_{nm}(X_{nm}^{s\,*}) + \sum_{n=1}^{N} FI_n(U_n) + \sum_{n=1}^{N} \sum_{m=1}^{M_n} \lambda_{nm}^{s\,*} \times G_{nm}(X_{nm}^{s\,*}, U_n') \tag{9}$$

$$s = 1, \ldots, S.$$

$$\sum_{n=1}^{N} \sum_{m=1}^{M_n} \lambda_{nm}^{t\,*} \times G_{nm}(X_{nm}^{t\,*}, U_n') \le 0 \tag{10}$$

$$t = 1, \ldots, T.$$

The maximal installation limits are shown as (5) and (6). All U_n's have discretization constraints.

where

- Z : objective function value;
- s : master-slave iteration index if the slave level is feasible;
- t : master-slave iteration index if the slave level is infeasible;
- $X_{nm}^{s(t)*}$: subproblem primal solution vector, held as constant in the master problem, for year n case m in the s(t)-th master-slave iteration;
- U_n : new installation of var compensation including capacitor and inductor for year n;
- U_n' : summation of compensation U_n from the year 1 to the year n;
- $\lambda_{nm}^{s(t)*}$: subproblem dual solution vector, held as constant in the master problem, for year n case m in the s(t)-th master-slave iteration;
- S, T : total feasible and infeasible solution numbers for slave level problems.

The solution variables in the master problem only consist of new installations of var compensation. All solutions from the subproblems are parameterized in the master problem as the constraint coefficients in the Benders cuts as shown in (9) and (10).

A new Benders cut is generated with each new set of subproblem solutions. The cumulation of the Benders cuts has the effect of gradually excluding infeasible region (w.r.t. the total problem) from the master problem solution space.

MASTER PROBLEM SOLUTION

Each solution of the master problem is an optimal solution in a partially relaxed solution space of the complete problem. As such, the objective function values for the master problem are lower bounds on the global optimum (assuming convexity for the subproblems).

The master problem has integer constraints. However, rather than using integer programming method, we choose to optimize the master problem by augmenting LP with a simple rounding-up logic. Since the master problem would be solved repeatedly in the master-slave iteration, the simple logic would be much more effective than if it were applied after the entire master-slave iteration was completed. The effectiveness of the discretization logic could be observed from test results shown later.

BENDERS CUT

After each round of the subproblems optimization, a Benders cut, which coordinates the master and the slave levels, would be generated in the form of either (9) or (10), depending subproblems feasibility.

When all subproblems contained in the slave level have feasible solutions, the Lagrange multipliers for the binding var compensation constraints and the binding limits become parameters in the Benders cut, as shown in (9). The investment cost and the marginal benefit for each unit of var compensation in the equation supply the the necessary information for the master problem to improve var compensation solution.

When the slave level does not have feasible solution, a Benders cut in the form of (10) will be generated. It contains information about the amount of limit violations and the corresponding Lagrange multipliers.

The method described in [12] is used to solve the infeasible subproblems. Infeasibility is detected when the Lagrange multiplier exceed certain threshold. The method performs well when the problem is clearly infeasible; but when the problem is border-line infeasible, convergence suffers significantly. For cases which have relatively insignificant operating cost compared with the investment cost, the master problem would naturally give border-line infeasible var compensation to the slave level. Further improvements aimed at border-line infeasibility therefore have to be developed. They are discussed next.

SUBPROBLEM INFEASIBILITY

Infeasible subproblem solutions are often encountered as a result of the master problem optimizing in a solution space that is partially relaxed with respect to the total constraints. If the subproblem is clearly infeasible, the Lagrange multipliers could exceed the threshold level for detecting infeasibility relatively quickly (a few iterations). However, if the var compensation pattern prescribed by the master problem is border-line infeasible, the Lagrange multipliers for the subproblem converge slowly. When this occurs, it is difficult to decide when to terminate the iteration, and how to generate proper Benders cuts from the subproblem solutions.

To better handle border-line infeasibility, we first improve the logic to detect it. Instead of checking Lagrange multiplier values after the full solution has converged, we enhance the logic to check for limit violations and Lagrange multipliers as soon as the primal variables converged. This is based on the intuition that when the solution is border-line infeasible, a well defined solution exists for the primal variables but not for the dual variables.

When border-line infeasibility is detected, we would terminate the subproblem iteration and build an infeasible Benders cut eventually for that master-slave iteration. Violations in excess of constraint deadbands and their corresponding Lagrange multipliers are fully modeled as residual values in the infeasible Benders cut as shown in (10).

Significant improvement for the overall solution process is achieved with the enhanced handling of subproblem infeasibility. Test results are presented later.

IV. TESTS AND RESULTS

We have implemented the methodology and tested it on the Taiwan Power Company system. The system contains 217 buses, 27 voltage-regulating generators, and 105 LTC transformers for the base year. Taipower's standard bank size is 14.4 MVAR and 40.0 MVAR for capacitor and inductor, respectively. The maximum installation limit for each candidate bus depends on its space. For example, the maximum limits of the most of buses are 28.8 MVAR due to existing shunt capacitors. If the bus is new or without existing capacitor, the maximum limit is 57.6 or 72.0 MVAR.

Verification of the Decomposition

A concern with the Benders Decomposition is the legitimacy of decomposition: is the problem suitable for decompostion? and does the decomposition methodology correct? We are therefore interested to see if the problem could be solved to the same solution with and without using decomposition.

To solve the problem without decomposition, we use the Newton OPF, which had been enhanced to handle a complete single year, single case optimal var planning problem. The solution from the nondecomposed approach, which is based on Newton-OPF, is then compared with the solution from the decomposed approach.

The test problem has low voltage conditions initially: 12 bus voltage were below the minimum level of 0.95 p.u.. To correct for the low voltages, we allowed the existing LTC's and generator voltages to be adjusted as controllers, and also defined 13 buses as candidates for var installation. All variables were treated as continuous type to facilitate direct comparison of the results.

As shown in Table 1, the two approaches reach essentially the same solution. In particular, out of a choice of the 13 candidates, the same 3 buses were selected for var installation. The total amount of var installation for capacitors was 212.2 MVAR vs. 213.5 MVAR. The difference was less than 0.4%.

Table 1 Comparison of Optimal Var Compensation Solution from Two Different Approaches. (with and without decomposition)

Bus Name	MVAR Compensation without Decomposition	MVAR Compensation with Decomposition
Chukungh	0.0	0.0
Takuan h	0.0	0.0
Wanta	0.0	0.0
Chunkanl	72.0	72.0
Lotung 1	0.0	0.0
Wufengl	0.0	0.0
Changhua	68.2	69.5
T.C.CIH	72.0	72.0
Pulil	0.0	0.0
Chiayil	0.0	0.0
Shinyinl	0.0	0.0
Yunlinl	0.0	0.0
Peikangl	0.0	0.0
Total	212.2	213.5

Convergence of Generalized Benders Decomposition

Convergence pattern for the decomposition solution, in terms of the master level and the slave level solutions, is shown in Table 2. In this test, a set of initial installation pattern is fixed in the slave level at first. The total problem takes 5 master and 6 slave iterations to converge. The iterative count does not appear to be very sensitive to system size: similar numbers of iterations were taken when the program was tested on a 6-bus and 40-bus systems.

Table 2 Convergence Pattern of Benders Decomposition

Iteration Process	--MVAR Bus Compensation-- C'kan	C'hua	T.C.C	Others	Objective Value	
slave	-	-	-	-	11.22	-
master	0.0	0.0	0.0	0.0	-	1.147
slave	-	-	-	-	infea.	-
master	72.0	67.0	72.0	0.0	-	3.256
slave	-	-	-	-	infea.	-
master	72.0	68.1	72.0	0.0	-	3.267
slave	-	-	-	-	infea.	-
master	72.0	71.4	72.0	0.0	-	3.301
slave	-	-	-	-	3.323	-
master	72.0	69.5	72.0	0.0	-	3.303
slave	-	-	-	-	3.303	-
------ CONVERGE ------						

Referring to the above table, we note that several iterations are spent to fine tune the optimal var installation at Changhua. Such fine tuning would not be necessary when integer constraints are introduced.

If the convexity requirements are satisfied, then the master problem objective function values would be a monotonically non-decreasing sequence of lower bounds for the the total problem; and the subproblem objective function values would be the upper bounds. For this test problem, the upper and lower bounds eventually converged to the same value. It is a strong indication that the solution is indeed optimal [10].

Improved Handling of Infeasible Subproblem

When the subproblem is border-line infeasible, we could reduce the number of required subproblem iterations, and hence improving the overall solution speed, by including constraint residuals in the Benders cut. By varying convergence tolerance for the Lagrange multiplier, we are able to terminate subproblem iteration at different spots and examine the impact on overall solution process.

Results from testing with two different tolerance levels for border-line infeasible condition are presented in Table 3. It contains the final optimal var compensation pattern, the number of subproblem solved, and the numbers of Newton iteration for each subproblem.

Table 3 Effect of the Different Convergence Tolerances for Border-line Infeasible Condition of Slave Level.

	Tight Tolerance	Relaxed Tolerance
Chunkanl	72.0	72.0
Changhua	69.5	69.5
T.C.CIH	72.0	72.0
Other	0.0	0.0
	(MVAR Compensation)	
No. of Subproblem Solved	6	6
No. of New. Iter. for each subp.	6, 19, 30, 47 9, 2 (total 113)	6, 19, 12, 13 18, 3 (total 71)

We could observe from Table 3 that the same optimal var compensation pattern was reached with the two different tolerance levels. Although these two cases required the same number of running Newton-OPF, the case with loose tolerance required much fewer Newton iterations (113 vs. 71), and thus converged much faster.

Coordination of Var Compensation for Multi-Cases

An indication for effective var compensation is that a given compensation schedule satisfies the requirements for different operating conditions. While a planner could often determine the optimal var schedule associated with individual cases, it is much more difficult to coordinate across multiple cases simultaneously. With the GBD approach, multi-case coordination could be easily achieved, as illustrated below.

Figure 2 shows a portion of the Taiwan HV grid: voltage security for two separate contingencies is to be maintained. One contingency involved line outage between Hsinchu and Nanhu, the other involved line outage between Tienlun and Wengtuz.

When the two contingencies were analyzed separately, the first contingency required 69.5 MVAR (in continuous solution) at Nanhu; the second contingency required 78.5 MVAR at Wengtuz. When the two cases were analyzed together by using the GBD approach, the optimal var installation was 29.3 MVAR at Nanhu, 20.4 MVAR at Miaoli and 39.3 MVAR at Wengtuz. From the reduced total var requirement (from 148.0 MVAR to 89.0 MVAR) and the selection of the centrally-located Miaoli substation, we can observe that the methodology could indeed handle multi-case coordination.

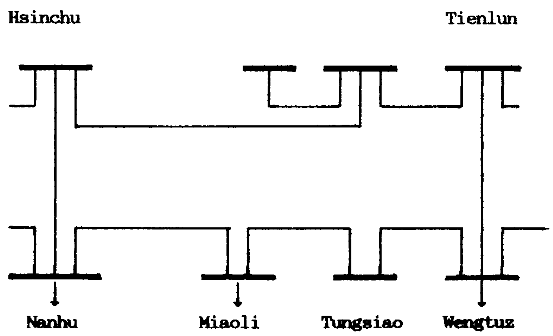


Figure 2 Portion of Taiwan Power System.

Multi-year Multi-case Study

This section contains results of a comprehensive var planning study that modeled multiple years, multiple cases and discretized var variables. The purpose of this test is to show that we could determine the year by year var installation pattern, that would be optimal (and feasible) with respect to the different cases in different years. The effect of the simple discretization logic embedded within the GBD would also be demonstrated.

The planning scenario contained a separate base case and different contingency for each of the three studied years. All var compensations were discretized into integer number of 14.4 MVAR blocks. To simulate the practice of delaying investment until the investment is needed to maintain system security, we assigned progressively lower cost for var compensation occuring in the future years.

To give an indication of the effectiveness of the discretization logic, we also present the results from a study in which no discretization is performed. Both sets of results are presented in Table 4.

Based on test results like the one shown in Table 4, we feel the discretization logic is adequate for this type of var planning studies. For reference purposes, the same set of cases were also studied by an experienced system planner using a power flow program. After several days, the answer he came up with was 37 banks, located in generally the same set of candidate buses. This gave some credibility to the overall var planning methodology and program.

Table 4 Comprehensive Multi-year, Multi-case Var Compensation Results.

Bus Name	MVAR compensation 1st year	2nd year	3rd year
	(continuous/discrete 14.4 MVAR blocks)		
Lunchoul	0.0/ 0.0	0.0/ 0.0	22.9/28.8
Tatungl	0.0/ 0.0	0.0/ 0.0	28.8/28.8
Nanhul	28.8/28.8	0.0/ 0.0	0.0/ 0.0
Miaolil	14.0/14.4	0.0/ 0.0	0.0/ 0.0
Chiayil	0.0/ 0.0	28.8/28.8	0.0/ 0.0
Shinyinh	0.0/ 0.0	39.8/57.6	0.0/ 0.0
Shinyinl	0.0/ 0.0	28.8/28.8	0.0/ 0.0
Tainanl	0.0/ 0.0	28.8/28.8	0.0/ 0.0
Tainanh	0.0/ 0.0	22.2/ 0.0	0.0/ 0.0
Annanh	0.0/ 0.0	0.6/14.4	0.0/ 0.0
Annanl	0.0/ 0.0	28.8/28.8	0.0/ 0.0
Yunlinh	0.0/ 0.0	15.7/ 0.0	0.0/ 0.0
Yunlinl	0.0/ 0.0	28.8/28.8	0.0/ 0.0
Shansanl	0.0/ 0.0	28.8/28.8	0.0/ 0.0
Peikangh	0.0/ 0.0	26.9/43.2	0.0/ 0.0
Peikangl	0.0/ 0.0	28.8/28.8	0.0/ 0.0
Yunhanl	0.0/ 0.0	28.8/28.8	0.0/ 0.0
Others	0.0/ 0.0	0.0/ 0.0	0.0/ 0.0
	42.8/43.2 3 banks	335.6/345.6 24 banks	51.7/57.6 4 banks

V. CONCLUSIONS

An integrated methodology for multi-year and multi-case var planning study is described. The method contains an effective application of the Newton method to slove the OPF subproblem created by the Generalized Benders Decomposition. An effective discretization logic embedded within the master-slave iteration is also described. Test results are presented to demonstrate the overall effectiveness of the methodology.

The results of the research presented here have been applied in a follow-up study of the voltage instability problem. Preliminary indication are mixed: the Newton OPF for slave level would identify slowly to a consistent set of binding constraints due to severe constraint violations. But once converged, a proper Benders cut would be generated to allow smooth convergence of the master-slave iteration. A paper will be presented when this extended work is finished.

VI. REFERENCES

1. Kishore, A. and Hill, E.F., 'Static Optimization of Reactive Power Sources by Use of Sensitivity Parameters', IEEE Trans. on Power App. and Syst., Vol. PAS-90, May/June 1971, pp. 1166-1173.

2. H. H. Happ and K. A. Wirgau, 'Static and Dynamic Var Compensation in System Planning', ibid, Vol. PAS-97, Sept./Oct. 1978, pp. 1564-1578.

3. A. Hughes, G. Jee, P. Hsiang, R.R. Shoults and M.S. Chen, 'Optimal Reactive Power Planning', ibid, Vol. PAS-100, May 1981, pp. 2189-2196.

4. R.A. Fernandes, F. Lange, R.C. Burchett, H.H.Happ and K.A. Wirgau, 'Large Scale Reactive Power Planning', ibid, Vol. PAS-102, May 1983, pp. 1083-1088.

5. W.C. Merritt, C.H. Saylor, R.C. Burchett and H.H. Happ, 'Security Constrained Optimation - A Case Study', IEEE PES Summer Meeting, Paper 636-4, 1987.

6. K.Y. Lee, J.L. Ortiz, Y.M. Park and L.G. Pond, 'An Optimization Technique For Reactive Power Planning of Subtransmission Network under Normal Operation', IEEE Trans. on Power System, Vol. PWRS-1, No.2, May 1986, pp. 153-159.

7. W.M. Lebow, R. Rouhant, R. Nadira, P B. Usoro, R.K. Mehr, D.W. Sobieski, M.K. Pal, M.P. Bhavaraju, 'A Hierarchical Approach to Reactive Volt Ampere(Var) Optimation in System Planning', IEEE Trans. on Power App. and Syst., Vol. PAS-104, August 1985, pp. 2051-2057.

8. R. Nadira, W.M. Lebow and P.B. Usoro, 'A Decomposition Approach to Preventive Planning of Reactive Volt Ampere(Var) Source Expansion', IEEE Trans. on Power System., Vol. PWRS-2, No.1, Feb. 1987, pp. 72-77.

9. S. Granville, M.V.F. Pereira and A. Monticelli, 'An Integrated Methodology for Var Source Planning', IEEE PES Winter Meeting, Paper 039-1, 1987.

10. A.M. Geoffrion, 'Generalized Benders Decomposition', Journal of Optimization Theory and Application, Vol. 10, No. 4, 1972, pp. 237-262.

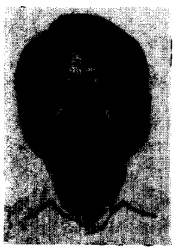
11. D.I. Sun, B. Ashley, B. Brewer, B.A. Hughes and W.F. Tinney , 'Optimal Power Flow by Newton Approach', IEEE Trans. on Power App. and Syst., Vol. PAS-103, Oct. 1984, pp. 2864-2875.

12. D.I Sun, T.I Hu, G.S. Lin, C.J. Lin and C.M. Chen, 'Experiences with Implementing Optimal Power Flow for Reactive Sheduling in the Taiwan Power System', IEEE PES Summer Meeting, Paper 505-1, 1987.

Biography

Ying-Yi Hong (IEEE student member since 1988) was born in Kao-Hsiung, Taiwan, R.O.C. on December 15, 1961. He received his BSEE degree from Taiwan Private Christianity Chung Yuan University in 1984 and MSEE degree from Taiwan National Cheng Kung University in 1986. He now is a Ph.D candidate in E.E. in Taiwan National Tsing Hua University.

His special areas of research are power system analysis, control and dispatch; as well as computer science, software engineering and algorithm.



David I. Sun (IEEE member) was born on Oct. 21, 1951. He received his BSEE and MSEE degree from Resselaer Polytechic Institute in 1974 and 1976, and Ph.D from the University of Texas at Arlington in 1980.

He worked at ESCA Corp. in Bellevue, Seattle from 1980 to 1985. During that time period, he was primarily involved with developing advanced network applications for Energy Management System. From Sep. 1985 to Sep. 1988, he was a visiting faculty at the National Tsing Hua University in Taiwan, where he taught various power system engineering courses and conducted joint research projects with the Taiwan Power Company. Dr. Sun re-joined ESCA in Sep. 1988.

Shin-Yeu Lin received the B.S. degree in electronics engineering from Chiao-Tung University, Taiwan, R.O.C., and the M.S. degree in electrical engineering from the University of Texas at El Paso in 1975 and 1977, respectively, and the D.Sc. degree in systems science and mathematics from Washington University, St. Louis, Missouri in 1983.

Since 1983, he had been teaching in Chiao-Tung University and subsequently in Washington University. During 1985-1986 he worked in GTE Laboratories, Waltham, Massachusetts as a senior member of Technical Staff. Since November 1986 he has been an Associate Professor in Department of Control Engineering, Chiao-Tung University.

His major research interests are large scale power system analysis, optimization theory and its application, and large scale network.

Chia-Jen Lin (IEEE senior member since 1987) was born in Taipei, R.O.C. in 1926. He received B.S. degree in E.E. from Technical Institute of Taiwan in 1949.

He has been working for Taiwan Power Company since 1951. His major field was designing and planning of transmission and substation system. Currently, he is the Director of System Planning Department of the Company.

He is a registered professional electrical engineer of R.O.C., Permanent Member of both the Chinese Institute of Engineers and the Chinese Institute of Electrical Engineering, and a member of CIGRE.

Discussion

N. I. Deeb (Control Data Corporation), and **S. M. Shahidehpour** (Illinois Institute of Technology): The authors are to be congratulated for this work. The optimal VAR planning is one of the most important problems in power systems, and the application of the Benders decomposition method is based on the structure of this complex problem.

Could the authors discuss the following points:

- The addition of new VAR sources is restricted to a set of candidate buses. The proposed method starts with a selected initial candidate set, and this set would not be updated during the optimization process. However, the selection of buses at which reactive sources can be added is very critical in the planning process. A poorly selected candidate set may lead to the infeasibility of the problem or to an uneconomical overall solution.

Authors comments on this point and the basis for the selection of candidate buses in their example will be appreciated. If the initial candidate set is to be updated, at what stage of the process and how would it be implemented?

- Several linear programming based algorithms have recently been proposed to solve the problem of minimizing the MW losses in the system. Our research in this respect has considered the application of linear decomposition techniques to solve the problem [a]. Did the authors consider the possibility of implementing linear programming in solving the subproblems in their proposed method?
- Introducing contingency cases in the optimization problem is based on the type of actions adopted in the system operation (preventive or corrective). This type of actions would result in various limitations on the number of contingency constraints that would be introduced in the problem. The paper does not reflect this problem. Would the authors comment on this point?

Reference

[a] Nedal Deeb and S. M. Shahidehpour, "Linear Reactive Power Optimization in a Large Power Network Using the Decomposition Approach," paper #89 SM 695-8 PWRS, presented at the 1989 IEEE/PES Summer Meeting.

Manuscript received August 7, 1989.

Ying-Yi Hong: The author would like to thank the discussers for their valuable comments on the paper.

1. The selection of candidate set depends primarily on the physical characteristics of the power system; it also depends to a less significant degree on mathematical basis. For every bus in the system, the Newton OPF computes a reactive Lagrange multiplier, which could be used as a basis for modifying the candidate set. The proposed method could be enhanced, if necessary, to modify the candidate set automatically.
2. Both linear programming and Newton method could be used to solve the slave level. The most significant reason for using Newton OPF in slave level is its capability in handling infeasible or border-line infeasible solution.
3. The proposed method models corrective contingencies directly. Functional constraints representing contingency limits need to be added in the slave base case problem in order to enforce preventive contingency.

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