Optimization Method for Reactive Power Planning by Using a Modified Simple Genetic Algorithm

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***Abstract*— This paper presents an improved simple genetic algorithm developed for reactive power system planning. The successive linear programming (LP) is used to solve operational optimization sub-problems. New population selection and generation method which makes the use of Benders' cut is presented in this paper. It is desirable to find the optimal solution in few iterations, especially in some test cases where the optimal results are expected to be obtained easily. However, the simple genetic algorithm has failed in finding the solution except through an extensive number of iterations. Different population generation and crossover methods are also tested and discussed. The method has been tested for 6 bus and 30 bus systems to show its effectiveness. Further improvement for the method is also discussed.**

Key-Words: Reactive Power Planning, Optimization, Benders Decomposition, Simple Genetic Method.

I. INTRODUCTION

The reactive power, or VAR, planning problem is a nonlinear optimization problem. Its main object is to find the most economic investment plan for new reactive sources at selected load buses which will guarantee proper voltage profile and the satisfaction of operational constraints. Usually the planning problem is divided into operational and investment planning subproblems. In the operational planning problem the available shunt reactive sources and transformer tap-settings are optimally dispatched at minimal operation cost. In the investment planning problem new reactive sources are optimally allocated over a planning horizon at a minimal total cost (operational and investment).

During the past decade there has been a growing concern in power systems about reactive power operation and planning. Recent approaches to the VAR planning problem are becoming very sophisticated in minimizing installation cost and for the efficient use of VAR sources to improve system performance. Various mathematical optimization formulations and algorithm have been developed, which, in most cases, by using nonlinear [10], linear [6], or mixed integer programming [11], and decomposition method [15-18]. More recently, simulated annealing[19] and genetic algorithm [22,23] have also been used. With the help of powerful computers, it is now possible to do a large amount of computation in order to achieve a global optimal instead of a local optimal solution.

Simulated annealing method is a random search method. Hsiao et al. [18] provided an approach for the simulated annealing method using the modified fast decoupled load flow. However, only the new configuration (VAR installation) is checked with the load flow, and existing resources such as generators and regulating transformers are not fully exploited. Simple Genetic Algorithm (SGA) method is a powerful optimization technique analogous to the natural genetic process in biology. Theoretically, this technique converges to the global optimum solution with probability one, provided that certain conditions are satisfied. The SGA method is known as

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a robust optimization method. It is useful especially when other optimization methods fail in finding the optimal solution. However, it often requires too many repeated computations in obtaining final results.

In order to obtain a good result for reactive power generation planning problem, a synthetic optimization procedure is presented by combining two optimization methods together, random search and optimization algorithm.

This paper presents an improved method of operational and investment planning by using a simple genetic algorithm combined with the successive linear programming method. The Benders' cut are constructed during the SGA procedure to enhance the robustness and reliability of the algorithm. The method takes advantage of both the robustness of the SGA and the accuracy of conventional optimization method.

The proposed VAR planning approach is in the form of a two level hierarchy. In the first level, the SGA is used to select the location and the amount of reactive power sources to be installed in the system. This selection is passed on to the operation optimization sub-problem in the second level in order to solve the operational planning problem. It is a common practice to use a successive linear programming (LP) formulation to improve the computation speed and to enhance the computation accuracy; the LP method is fast and robust. The operational planning problem is decoupled into weakly coupled real (P) and reactive (Q) power optimization modules; and the successive linearized formulation of the P-Q optimization modules speeds up computation, and allows the LP to be used in finding the solution of the nonlinear problem [14]. The dual variables in the LP are transferred from the P-Q optimization modules to the SGA module in the first level to set up the Benders' cut for investment planning. This hierarchical optimization approach allows the SGA to obtain correct VAR installations, and at the same time satisfy all the operational constraints and the requirement of the minimum operation cost.

II. REACTIVE POWER PLANNING

The reactive power planning problem is to determine the optimal investment of VAR sources over a planning horizon[16]. The cost function to be minimized is the sum of the operation cost and the investment cost. The investment cost is the cost to install new shunt reactive power compensation devices for the system. The fuel cost for generation is the only operation cost to be considered in this paper.

A. Investment-Operation Problem

The reactive power planning problem involves both operation and investment costs, and it can be written in the following form:

$$\min_{Y,U} \; f(Y,U)) = L_o(Y) + L_u(U) \tag{1a}$$

subject to

$$G_1(Y,U) \le 0 \tag{1b}$$

$$G_2(U) \le 0, \tag{1c}$$

where

$Y = [P^T, V^T, N^T]^T$: vector of operational variables

P : vector of real power generations,

V : vector of bus voltage magnitudes,

N : vector of tap-settings,

U : vector of investment variables

$L_o(Y)$: operation cost

$L_u(U)$: investment cost

$G_1(.)$: constraint involving both Y and U

$G_2(.)$: constraint involving U only.

Equation (1a) consists of investment and operation cost. Equation (1b) are coupled constraints for operation and investment variables. It includes load flow balance and other important operational constraints. Equation (1c) includes constraints relative to only investment variables.

B. Benders Decomposition Formulation

The operation cost is nonlinear, and the investment cost can be assumed to be linear with respect to the amount of newly added reactive power compensation. According to this assumption the minimization problem (1) can be expressed in a nonlinear programming formulation:

$$\min_{Y,U} \; C^T U + f(Y) \tag{2a}$$

subject to

$$H(Y) + BU \le b_1 \tag{2b}$$

$$DU \le b_2, \tag{2c}$$

where

Y : vector of operation variables

U : vector of investment variables

C : vector of cost coefficients

B, D : matrices of constraints

f, H : cost and constraint functions, respectively.

b_1, b_2 : vectors of constraints.

Because of the structure of the constraints, it is quite natural to consider two level hierarchical approach to solve the problem. That is, use the SGA to select the device and amount, and use an optimization method to obtain optimal results under the given installation.

In this paper the generalized Benders decomposition (GBD) method [20] is used in the SGA module in setting up a Benders' cut in order to improve the convergence characteristics. The procedure is as following:

(i) Assuming a feasible investment U, the feasible decision Y is obtained by solving the Y (operation) subproblem:

$$\min_{Y} f(Y) \tag{3a}$$

subject to

$$H(Y) \leq b_1 - BU. \tag{3b}$$

(ii) Having found optimal Y from the first stage, the decision for the feasible investment U is obtained by solving the U (investment) subproblem:

$$\min_{U,\sigma} \quad Z = C^T U + \sigma \tag{4a}$$

subject to

$$DU \leq b_2 \tag{4b}$$

$$W(U) \leq \sigma, \tag{4c}$$

where σ is an upper limit varable, and $W(U)$ is called the *Benders' cut* and is a function which supplies information concerning the capacity decision U in terms of the operation feasibility. Then the problem would determine a solution (U, Y) that would minimize the global function (2a).

The Benders decomposition method builds the function $W(U)$ based on the solution of the Y subproblem. In nonlinear optimization, $W(U)$ can be determined if we observe that the simplex multiplier vector associated with the first stage (Y subproblem) is the basic feasible solution for the dual problem. Therefore,

$$W(U) = v(U^k) + \lambda^k(BU^k - BU), \tag{5}$$

where v(.) is the optimal operation cost with the installation of U^k.

The dual solution λ^k is the simplex multiplier associated with the constraint in the operation subproblem, where k is the iteration number. Since the revised simplex method is used for solving the operation subproblem, λ^k is obtained as a by-product and new constraints, each corresponding to a different investment installation, are established.

From equations (4a) to (4c), it can be seen that λ_i^k presents the change of the cost caused by the unit change in investment for unit i. If $\lambda_i^k > 0$ then $U_i > U_i^k$ is helpful in generating a new member of population, which may decrease the total cost Z. If only one constraint is considered, a decreasing direction similar to the steepest descent method can be found. The Benders' cut is viewed as a coordinator between investment and operation subproblems, and the GBD method iterates between the two. At each iteration a new constraint is added into $W(U)$ to form a new constraint set.

III. SIMPLE GENETIC ALGORITHM

The simple Genetic Algorithm consists of a population of bit strings transformed by three genetic operations: selection or reproduction, crossover and mutation. Each string represents a possible solution, with each substring representing a value for a variable of interest. The algorithm starts from an initial population generated randomly. A new generation is generated by using the genetic operations considering the fitness of a solution which corresponds to the objective function for the problem. The fitnesses of solutions are improved through interations of generations. When the algorithm converges, a group of solutions with better fitnesses is generated, and the optimal solution is obtained.

A. String Representation

String representation is an important factor in solving the the VAR planning problem using the SGA. In order to accomodate different representations of object parameters, i.e., the investment variables, the following representation method is used.

A string consists of sub-strings; the number of sub-strings is equal to the number of total candidate buses for adding capacitors or inductors. Each sub-string is in the form of binary corresponding to the amount of capacitive or inductive VAR. This binary representation is certainly not unique, but it is simple to implement. For example, the 3 bit binary for a unit can represent $2^3 = 8$ different amounts of installation for capacitive or inductive VAR. On the other hand, the 4 bit represents $2^4 = 16$ choices.

B. Genetic Operations

1) Initial population generation - Initial population of binary strings is created randomly. Each of the strings represents one feasible solution satisfying constraint (1c).

2) Fitness evaluation - The solution strings and each candidate solution is tested in its environment. The fitness of each candidate solution is evaluated through some appropriate measure such as the inverse of the cost function Z. The algorithm is driven

towards maximizing this fitness.

3) Selection and reproduction - Selection and reproduction create a new population from old population. A set of old strings are selected to reproduce a set of new strings according to the probability determined by the simulated spin of weighted roulette wheel. The roulette wheel is biased with the fitness of each of the solution candidates. The wheel is spun N times where N is the number of strings in the population.

4) Crossover - Crossover is performed on two strings at a time that are selected from the population at random. It involves choosing a random postion in the two strings and swapping the bits that occur after this position. Crossover can occur at a single postion (single crossover), or at a number of different positons (multiple crossover). Crossover can be performed in different methods. Two different means are used in this paper: Tail-tail and head-tail crossovers.

The tail-tail crossover tends to change less significant bits. On the other hand, the head-tail crossover gives more chance of changes by changing more significant bits. The crossover methods can be changed during iterations: the head-tail crossover can be used in early generations and then switched to tail-tail crossover in later generations for fine tuning.

5) Mutation - Mutation is performed sparingly, typically every 100-1000 bit transfers from crossover, and it involves selecting a string at random as well as a bit postion at random and changing it from a 1 to a 0 or vice-versa. It is used to escape from a local minimum. After mutation, the new generation is complete and the procedure begins again with fitness evaluation of the population.

IV. A SOLUTION ALGORITHM FOR VAR PLANNING

The planning methodology developed in the paper is simulated for reactive power planning problem. The problem is decomposed into investment and operation subproblems, and solved iteratively until convergence [16].

The operation subproblem is again decomposed into economic real (P) and reactive (Q) power dispatch problems to minimize the fuel cost function [13],[14]. In the P module optimal values of real power generation, and in the Q module the optimal values of bus voltage magnitudes and transformer tap-settings are obtained. In addition, the optimal values of reactive power dispatched by the generators and compensators are also obtained.

In each population, total operation and investment costs are calculated for each investment. The fitness is simply the inverse of this total cost. The ratio of the average fitness and the maximum fitness of the population is computed and generation is repeated until

$$\frac{averagefitness}{maximumfitness} \geq AP,$$

where AP is a given number that represents the degree of satisfaction. If the convergence has been reached at a given accuracy, then optimal values for investment are found. Other crietria, such as the difference between the maximum and minimum fitnesses and the rate of increase in maximum fitness, can also be used as the termination criteria. Another possibility is to stop the algorithm at some finite number of generations and designate the result as the best fit from the population.

The iterative process is as follows:

Step 1. Initial population generation - compute the fitness of each string according to operation sub-problem results.

Step 2. Generate new population - typical SGA methods, reproduction, crossover and mutation, are used. The Benders' cut is used on a subset of strings to obtain one new and better member of the population.

Step 3. Compute the fitness of the new generation.

Step 4. If convergence condition is satisfied, stop computation. Otherwise, return to Step 2, and begin a new generation.

The most important step is Step 2. A new population is generated according to the fitness of the old population through the simulated spin of a weighted roulette wheel in the SGA[21]. Some modification are made to the SGA for our planning problem, resulting in a modified SGA(MSGA):

(1) In the GBD, the iteration procedure is an alternate computation between investment and operation untill convergence is reached. The Benders' cuts are selected and constructed from old population. It is used to obtain a new member of population. The number of cuts can be adjusted as a part of the procedure. Some better fitted strings and some worse fitted strings are selected to construct the cuts. The Benders' cut helps in narrowing down the space of possible solutions, and thus speeds up the convergence.

(2) An abandoning rate is considered in giving up some poor alternatives by assorting the fitness of the alternatives.

(3) Different crossovers are also considered, that is, the tail-tail crossover and head-tail crossover, and the crossover position is selected randomly. The head-tail crossover can also be used in producting new strings from two identical parents.

In the original SGA, only the fitness value resulting from the operation subproblem is used to generate new generation. However the new population generated only by its fitness is random and blind. By using the Benders' cut, which makes use of both the dual variable information and the cost function, a new and better string can be found. If this new string is a good one (it may be the best one), i.e., it has a higher fitness value, it will survive to the next generation. Otherwise, it will likely die afterwards. In this method, the robust characteristics of the SGA can still be maintained; at the same time it increases the chance to find the optimal result faster. The Benders' cut can be set up without difficulty because all variables are made avaible when the operation optimization sub-problem is solved.

V. SIMULATION RESULTS

The systems tested and described here are the 6- and 30-bus networks. The emphasis is on the effectiveness of the technique and validity of results. The following parameters are used for SGA program:

population size: 25
mutation rate: 0.01
crossover rate: 1.0
abandoning rate 0.9
parameter resolution: 3 bits per substring

A. The 6-bus System

The 6-bus system given in [14] is considered, which has two generators at buses 1 and 2, and two load buses, 4 and 6, are used for shunt reactive compensation. The initial load flow results show that, with no reactive compensation there are under-voltages at load buses 3 through 6. Thus the reactive power supply from generators is not adequate to maintain the required voltage profile.

Table I shows the maximum, minimum and average fitnesses obtained by the simple genetic method (SGA) and modified simple genetic method (MSGA). Both methods give the same final results. However, the MSGA method needs less iterations than the SGA method.

After the reactive power planning is completed, the total reactive power compensation is summarized in Table II. It is observed that the voltage profile is within the operating range of 0.90–1.15 p.u. Both voltage limits are satisfied. The total cost is decreased from $619.53 to $390.78, a decrease of 36.9%. The final operation cost for the optimization without capacitor investment is $397.78, higher than the optimal result. The column for Test 2 is corresponding to the result obtained by using the Benders decomposition method. The total cost is also higher than that of the modified SGA method.

Table I. The fitness values for the 6-bus system

Method	Gen.		min	Ave.	max
SGA		initial	0.2526	0.2543	0.2559
	11	Final	0.2556	0.2558	0.2561
MSGA		initial	0.2526	0.2543	0.2559
	9	final	0.2547	0.2556	0.2561

Table II. Summary of results for the 6-bus system

Var.	limits Lower	upper	Initial state	Test 1 Result	Test 2 Result	Test 3 Result
V_1	1.0	1.1	1.00	1.1	1.065	1.032
V_2	1.0	1.15	1.00	1.15	1.150	1.150
V_3	0.9	1.0	0.78	0.932	0.948	0.983
V_4	0.9	1.0	0.88	0.966	0.995	0.995
V_5	0.9	1.0	0.82	0.968	0.995	0.996
V_6	0.9	1.0	0.87	0.946	0.979	0.995
P_1	10.0	100.0	94.8	53.68	52.67	52.40
P_2	50.0	100.0	50.0	100.00	100.00	100.00
Q_1	-20.0	100.0	53.84	67.535	33.06	14.097
Q_2	-20.0	100.0	25.19	18.047	12.14	8.930
C_4	0.0	30.0	0.0	0.0	20.0	25.0
C_6	0.0	30.0	0.0	0.0	20.0	30.0
Total cost($)			619.53	397.78	391.35	390.78
Losses(MW)			9.83	18.68	17.70	17.39

Test 1 - Operation optimization without investment.
Test 2 - Operation optimization with investment by Benders decomposition method only.
Test 3 - Operation optimization by using MSGA.

B. IEEE 30-bus System

For the IEEE 30-bus system [14], there are 6 generator buses. Seven buses are selected to add capacitors. Each candidate bus has 3 bits for parameter resolution which can represent 8 different values for installation.

The length of the string is 21 bits and the population size is 25.

Initial optimization is run for operational variables. The result shows that the system can maintain all operation constraints without any new capacitor installed, but at a higher cost. In order to test the effectiveness of the program high unit installation cost is used. It was anticipated that the SGA method should find an optimal result after certain generations and in which case additional installation should be zero.

Fig. 1 shows the iteration result for the test case using the MSGA with Benders' cut added. There were the total of 264 crossovers and 104 discards for the strings with bed fitness values.

Fig. 2 shows the iteration result for the test case using only the SGA, where there were 325 crossovers and 141 discards.

It can be seen that when the Benders' cuts are added for the MSGA, only 2 generations are needed to find the optimal result. After that the optimal results are still maintained during later iterations.

As indicated in Fig. 2, the SGA method needs 18 generations to find the final result. Due to random search, the optimal result can only be reached after a considerable number of iterations. The convergence procedure is slower than the MSGA method.

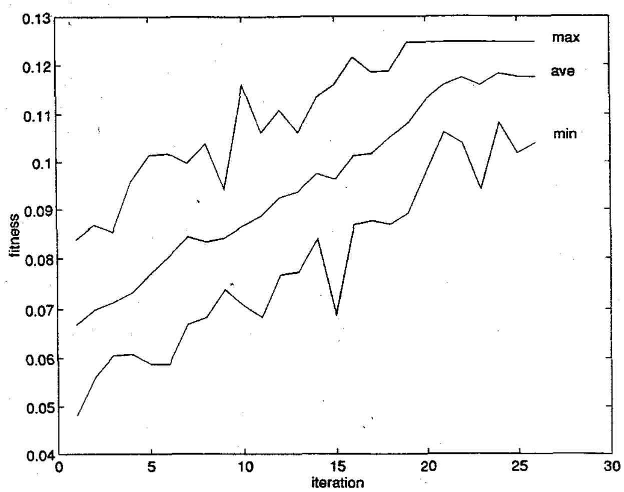

Fig. 1. MSGA iteration result.

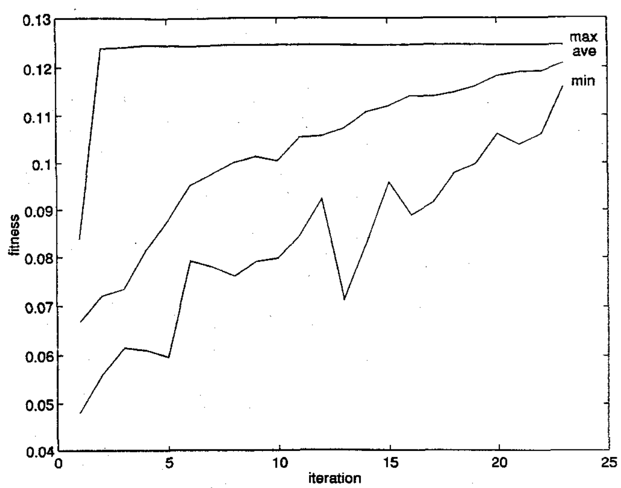

Fig. 2. SGA iteration result.

VI. CONCLUSIONS

A synthetical method of reactive power planning is presented. Different from the conventional SGA, which mainly uses the objective function for its fitness evaluation, the approach presented in this paper, MSGA, makes use of not only the objective function but also the dual variable information. The SGA is a random search algorithm and useful in finding the global optimal solution. The new formulation of the Benders method for investment-operation decomposition improves the robustness of the random algorithm.

The voltage profile throughout the planning period was improved from the under-voltages seen in the initial load flow to the required operation range. It was also seen that new shunt capacitors are installed at or near load buses that exhibit under-voltage violation. Our test shows that the MSGA method is robust in algorithm and gives good results which include the global minimum as a solution.

The SGA needs a higher cpu time compared with an analytical optimization method. However, the SGA is flexible, robust, and easy for modification. There is no need of assumptions for linearity, convexity, and so on. As it is shown, the method can be easily combined with other methods. including heuristic experience. With the help of high speed computers, more efficient optimization methods for operation sub-problem, and the parallel nature of the SGA, the MSGA promises as a useful tool for planning problems.

VII. ACKNOWLEDGEMENTS

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BIOGRAPHIES

<u>Kwang Y. Lee</u> received B.S.E.E. degree from Seoul National University, Korea, in 1964, M.S. degree from North Dakota State, Fargo in 1968, and Ph.D. degree from Michigan State, East Lansing in 1991. He has been with Michigan State, Oregon State, Univ. of Houston, and Pennsylvania State University, where he is a Professor of Electrical Engineering. His interests are power systems operation and planning, expert systems, and intelligent control of power plant.

<u>Xiaomin Bai</u> received B.S.E.E. from Tshinghua University, Beijing, China in 1977, and M.S. and Ph.D. degrees from China Electric Power Research Institute in 1982 and 1988. He has been with EPRI, working in EMS and DMS projects. Since 1992, he has been with Penn State working on Optimal Reactive Power Planning project. Dr. Bai's interest includes power systems operation, expert systems, and state estimation.

<u>Young Moon Park</u> recieved B.S., M.S., and Ph.D. degrees from Seoul National University, Korea. Since 1959, he has been with Seoul National University, where he is a Professor of Electrical Engineering. He is the past President of Korea Institute of Electrical Engineers and is now Director of Korea Electrical Engineering Research Institute. Dr. Park's interest is in power systems operation and planning, expert systems, and power plant intelligent control.

Discussion

L.L. LAI and J.T. MA, (Energy Systems Group, City University, London EC1V 0HB, England, UK): The authors are to be congratulated for an interesting paper. It would be appreciated if the following points could be clarified:

1. The approach proposes a two-level search. Simple genetic algorithm (SGA) is used to select the location and amount of reactive power sources. Linear programming (LP) is used to solve the operational planning problem. Genetic algorithm is supposed to search for the global optimum. Does the approach mean that the local minimum problem is only in the first level search area? Have the authors compared these two search methods, GA and LP, in the second level optimization or any other optimization problem? The paper supposes that the conventional optimization method is more accurate than GA. Have the authors had any comparison to justify this conclusion?

2. What is the criterion used to decide the transfer from the first to second level search? Are there any iterations between the first and second levels? If there are iterations, how to coordinate the two levels to avoid the divergence and still keep the CPU time as short as possible? If there is no iteration, how to guarantee the optimal result?

3. Is the population size of 25 the same in both 6- and 30-bus systems which have different control variables?

4. The objective function in the first level is linear. However, the function in the second level is highly nonlinear. Is there any reason for GA to be used in the first level but LP used in the second level?

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Kwang Y. Lee, Xiaomin Bai, and Young-Moon Park, The Pennsylvania State University, Department of Electrical Engineering, University Park, PA 16802, USA.:

We thank the discussers for their comments and for their interest in our work. Our reply is as follows:

1) Power system reactive planning problem is a nonlinear programming problem since its objective function and constraints are nonlinear even though the investment cost for reactive compensation devices can be considered as linear. The linear programming (LP) method is used for the successively linearized models to find the optimal solution for the nonlinear operation problem. The genetic algorithm (GA) provides a systematic investment optimization method: It selects the compensation devices and their amounts (investment subproblem), and the operation optimization problem is solved by LP under the given installation (operation subproblem). The process is repeated until the global solution is found for the planning problem. Therefore, the GA is used to search for the global optimum. Since the total planning cost (operation and investment costs) is a nonlinear function of the investment variables, it can have many local minima, i.e., many choices of installations in the first level. We did not try to compare LP method with GA method in the second level (operation problem) in this paper. It is believed that the GA method can be used in some special OPF problems when linear programming or conventional nonlinear programming methods may fail in finding an optimal solution; such as when the objective function is non-convex in an economic dispatch problem. For our reactive planning problem, better results are obtained by the MSGA method compared to the conventional LP methods, as stated in Simulation Result, A and B in Section V.

2) In this two level construction, the first level concerns the search procedure for optimal installation, and the second level involves the operation optimization under the given installation. The results obtained in the second level are transferred to the first level in the GA calculation to evaluate the fitness of the selected installation in pursuit of better reactive planning alternatives. There is no iteration between the first and the second levels; rather, they together form an iteration. Here, an iteration simply corresponds to a new generation which represents a set of alternative planning solutions. The optimal solution can be reached at the final generation as stated in step 4 of Section IV.

3) The selection of population size depends on the number of control variables. However, the same population size is used for both the 6-bus and the 30-bus systems. In our experience, when the population size was decreased for the 6-bus test system, the MSGA method still found the same optimal result; however, more iterations were required compared to the results in Table I.

4) Again, the GA simply selects installations and LP makes use of the selected installations optimally. The result of LP is used in evaluating the fitness of the selection made by the GA. In other words, the GA is used in place of an *ad hoc* or random selection, while LP being used for a faster computation of the optimal operation cost as an input to the GA. The successive LP method is known to be robust for the nonlinear operation problem. Other operation optimization methods such as the Gradient Projection Method [13] can also be used in conjunction with the GA presented in the paper.

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