FEEDER RECONFIGURATION AND CAPACITOR PLACEMENT IN DISTRIBUTION SYSTEMS: AN APPROACH FOR SIMULTANEOUS SOLUTION USING A GENETIC ALGORITHM

RECONFIGURACIÓN Y UBICACIÓN DE CONDENSADORES EN SISTEMAS DE DISTRIBUCIÓN: METODOLOGÍA DE SOLUCIÓN SIMULTÁNEA USANDO ALGORITMOS GENÉTICOS

Horacio Díaz R.[1]   **Ildefonso Harnisch V.**[1]   **Raúl Sanhueza H.**[1]   **Romina Olivares R.**[2]

RESUMEN

Este trabajo presenta una metodología para la solución simultánea de los problemas de ubicación de condensadores y reconfiguración de alimentadores en sistemas eléctricos de distribución radiales, con el fin de mejorar el perfil de voltaje de la red y, al mismo tiempo, reducir los costos asociados a las pérdidas de energía y potencia. Considerando un perfil de carga dado, se propone un método de optimización usando un algoritmo genético para determinar el tamaño óptimo, ubicación, tipo y número de condensadores fijos o conmutables, así como los estados abierto/cerrado de las llaves (switches) seccionadoras y de interconexión. La formulación del problema considera la minimización de los costos totales, incluyendo costos fijos y variables de los bancos de condensadores. El método propuesto se ha probado en diversas redes y los resultados muestran que considerando ambos problemas simultáneamente los costos debidos a las pérdidas se pueden minimizar hasta un 10% más que tomando dichos problemas por separado. Se presentan los resultados obtenidos en un sistema IEEE de 16 barras y una red de distribución real de 733 barras.

Palabras clave: Sistemas de distribución, reconfiguración, ubicación de condensadores, algoritmos genéticos.

ABSTRACT

This paper presents an effective approach to simultaneous solution of capacitor placement and feeder reconfiguration for power-energy loss cost minimization and voltage profile enhancement in radial distribution systems. Considering a time variation load, an optimization method using a genetic algorithm is proposed to determine the optimal location and size of fixed and switchable capacitors, as well as the open/closed states of the sectionalizing and tie switches. Reduction of overall power and energy losses and capacitor costs are involved in problem formulation. The proposed approach is demonstrated using example systems from the literature and results show that taken into account both capacitor placement and feeder reconfiguration simultaneously can generate around 10% more energy and peak loss reduction than considering them separately. Simulations results are presented for a 16 bus IEEE system and for a 733 bus practical distribution network.

Keywords: Distribution systems, feeder reconfiguration, capacitor setting, genetic algorithms.

INTRODUCTION

The pressure to improve overall efficiency has forced utilities to seek greater efficiency in distributions systems; communication and computing technology allow remote supervisory and control of capacitor and reconfiguration switches. In turn, this allows cost-effective solutions to loss minimization without any violations of operational conditions (voltage limits, maximum currents, radial configuration).

The problem of loss minimization can be obtained by an optimal setting of capacitors and feeder reconfiguration.

Capacitor setting is the process to determine capacitor types, sizes, locations and control schemes; and is the most widely accepted mean of improving voltage profile, power factor correction and loss reduction in distribution networks, but other operational parameters are also improved, like the peak current flows on network laterals and the total peak MVA of the system.

[1] Escuela Universitaria de Ingeniería Eléctrica-Electrónica. Universidad de Tarapacá. Arica, Chile. E-mail: hdiaz@uta.cl; harnisch@uta.cl; sanhueza@uta.cl
[2] Codelco, División Codelco Norte. Mina Chuquicamata. Edificio institucional de Codelco Norte. 11 Norte 1291. Villa Exótica. Calama, Chile. E-mail: roliv22@codelco.cl

Feeder reconfiguration is the process to determine a radial topological structures of distribution feeder by changing the open /closed states of the sectionalizing and tie switches in order to reduce losses, increase system security and enhance power quality.

The difficulty to solve the presented problems makes them to be resolved in an independent way. For this reason most of the studies handled capacitor setting without considering feeder reconfiguration or handled reconfiguration problems without considering the capacitor addition.

Optimal capacitor setting has been investigated since the 60's, [1-13]. Early approaches were based on heuristic techniques applied to relaxed versions of the problem. In the 80's, Grainger [1] formulated a more rigorous approach based on a no linear programming model solved by gradient search, Baran [2] proposed a solution by Benders decomposition. In the 90's evolutionary computation were proposed as means of solving the capacitor setting problem; Sundhararajan [4] used genetic algorithm (GA) to select capacitor for radial distribution system, Chiang [3] proposed Simulated Annealing (SA), Huang [5] used tabu search, Lai [6] and Lee [7] used evolutionary programming to solve optimal reactive power planning problem. In the 2000's Gallego [9] proposed a hybrid method draw upon the tabu search, extended with features taken from GA and SA.

Feeder reconfiguration has been relatively recently studied, [14-23], due to advanced computing and control capabilities required for its study. One of the first works reported was presented by Merlin and Back [14]. It presents an integer-mixed non-linear optimisation model that is solved through the discrete branch and bound method. Due to the combinatorial nature of the problem, it requires checking a great number of configurations for a real-sized system

In the 80's Civanlar [15] used a heuristic method for the estimation of the loss reduction obtained by a particular switching option (Switch exchange method), Shirmohammadi [16] used other heuristic method based on the switches having the lowest current flow (sequential switch opening method). In the 90's evolutionary computation is also proposed to solving the feeder reconfiguration problem. Nara [17] present an implementation using GA, Cheng [18] used a SA approach and Hsiao [21] used evolutionary programming.

Only a few papers on loss minimization for simultaneous feeder reconfiguration and capacitor setting had been presented, [24-31]. In the 90's, Peponis [19] used a two steps heuristic procedure, one for obtain a feeder reconfiguration and other for determine fixed capacitor size and location, this procedure is repeated until the two steps produce the same configuration and capacitor arrangements; Jiang [24] used a two steps procedure too, the first one employed SA to optimise the switch configuration and the second one a discrete optimisation algorithm to optimal capacitor control. In the 2000's Su and Lee [25] presented a first approach for feeder reconfiguration and capacitor setting simultaneously using SA, but they do not consider energy losses neither capacitors costs; Rong [27] proposed a cross-iteration optimization method, by alternately performing feeder reconfiguration and capacitor control; Dong [29-30] proposed a improved adaptive genetic algorithm to optimizing capacitor switching and a simplified branch exchange for each genetic instance at each iteration of capacitor optimization algorithm. Chang [31] proposed an ant colony search algorithm (ACSA) showed that the performance of the ACSA method is better than those obtained by the SA and GA, but the approach only considering fixed capacitors.

This paper presents a genetic algorithm for optimal loss minimization of distribution systems under jointly optimal capacitor setting and feeder reconfiguration. The proposed methodology has the following characteristics:

- It solves a multi-objective optimization problem for capacitor setting and feeder reconfiguration simultaneously, considering operating and engineering constraints.
- It is applicable to large-scale distribution systems with comprehensive modelling of diverse distribution components; including loads represented by diverse voltage dependent models, fixed and switchable capacitors, sectionalizing and tie switches, transformer losses.
- It considers power losses and capacitors costs.
- It considers a non-iterative power flow method for losses estimation.
- It attains a higher quality solution than classical methods for loss reduction in distribution systems.

PROBLEM FORMULATION

Given a balanced radial distribution network with a known topological structure, the problem consists on finding, for each load level, an optimal capacitor setting and a radial network among all possible radial networks generated with the switch condition changes (reconfiguration) and all possible capacitors types considered (capacitor placement), that minimizes the power and energy losses and that does not infringe the networks load flows and

operational constraints. This is a combinatorial, non differentiable and a mixed integer non-linear optimization problem.

The simultaneous solution of the optimal reconfiguration and capacitor setting problem determines which network switches should be open and which closed as well as capacitor types, sizes, control and locations in order to reduce losses, to improve voltage profile and, in a more limited way, to increase feeder capacity, under different load curves conditions and satisfying equipment and operation constraints.

In this paper the objective function is formulated as minimization of costs and investments (C) over a time period T, including power losses and energy losses, then the objective is to reduce the energy losses and peak power losses (P_{Pmax}) on the system while striving to minimize the cost of capacitor in the system (C_c). The cost of a switch state condition change is not considered. The mathematical formulation is described in equation (1).

$$\min C = CE_p(T) + CP_p(T) + C_c \tag{1}$$

Subject to:

$$
\begin{aligned}
V_{\min} \leq V_i(t) \leq V_{\max} && i = 1,2,...n, \ 0 < t < T \\
I_j(t) \leq I_{\max_j} && j = 1,2,...(n-1), \ 0 < t < T \\
Q_{C_k}(t) \leq Q_{C_{\max}} && k = 1,2,....N_{cond}, \ 0 < t < T \\
Q_{C_k}(t) = Q_{Cdisp_m} && m = 1;2,....Nc_{disp} \\
N_{cond} \leq nc &&
\end{aligned}
$$

No feeder section can be left out of service and radial network structure must be retained.

Where:

$V_{\min}, V_{\max}$	: Upper and lower limit for bus voltage
$I_j, I_{\max\ j}$	: Current magnitude of branch j and upper limit
$Q_{Ck}, Q_{Cmax\ k}$	: k-th capacitor reactive power and upper limit
$Q_{Cdisp\ m}$	: m-th available level of capacitor reactive power
n	: The total number of buses
N_{cond}	: The Number of new capacitors
NC_{disp}	: The Number of available level for new capacitors
Nc	: Upper limit for new capacitors

The energy (CE_p) and active power losses (CP_p) costs associated to a particular network configuration are evaluated with the equation (2), (3), where Ke is the energy cost factor and Kp is the active power cost factor. To calculate the energy losses in the system, the load variations for a given period of time T are taken into account considering the load profile, using the load duration curve, Figure 1.

A set of simplified feeder-line flow formulations called "Simplified Power Summation Method" is employed to avoid complex power flow computation [20].
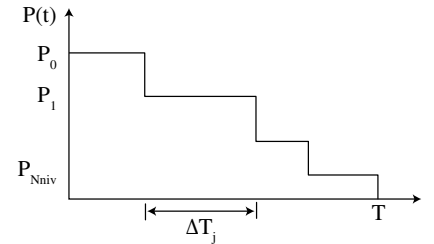
Figure 1. Discrete load duration curve.

$$CE_p(T) = Ke \sum_{j=1}^{Nniv} P_p(j) \cdot \Delta T_j \tag{2}$$

$$CP_p(T) = Kp \cdot Pp_{\max} \tag{3}$$

The formulation considers fixes (Q_{CF}) and switches (Q_{CV}) capacitors with a cost function such as Figure 2 shows.

Figure 2. Capacitors cost function.

From Figure 2, the total cost for new capacitor allocation (C_c) is given by equation (4).

$$C_C = \sum_{i=1}^{ncv} C(Q_{CVi}) + \sum_{i=1}^{ncf} C(Q_{CFi}) \tag{4}$$

GENETIC ALGORITHM

To solve the optimization problem formulated in equation (1) a genetic algorithm (GA) is proposed, the most popular form of Ev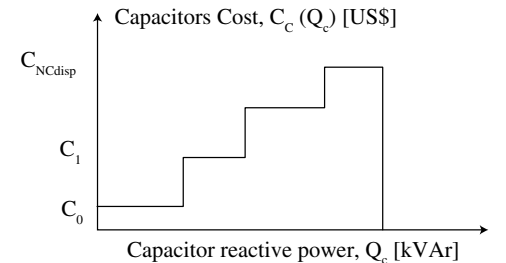olutionary Algorithms, inspired by the principle of evolution and, in essence, consists on a population of strings transformed by three genetic operators: selection, crossover and mutation. Each string (chromosome) represents a possible solution to the problem being optimized and each part of the string (sub string) represents a value for some variable of the problem (gene). These solutions are classified by an evaluation function, giving better values, or fitness, to better solutions. Each solution must be evaluated by the fitness function (having the role of environment) to produce a value. The pair (chromosome, fitness) represents an individual. The GA algorithm proposed in this paper has the following characteristics, [26].

Coding

Each possible radial distribution system with some switches states and capacitor setting is an individual in the population represented by a four sub string such as Table 1 shows.

Table 1.   Coding for the feeder reconfiguration and capacitor setting problem.

Sub string	Coding	Interpretation
Capacitor reactive power (Qc)	Integer	Vector with elements that designate the Qc for each load level.
Capacitor allocation	Integer	Vector with elements that designate the bus number for the capacitor placement.
Switches states	Binary	Vectors with the switches states for each load level
Network configuration	Integer	Predecessor vectors that designate the network topologic for each load level.

The sub string is as follows:

An integer code to the reactive power, considering fixed and switched capacitor for each load level.

An Integer code to designate the bus capacitor location.

A binary code to the switches states for each load level. If the binary value is zero the switch is open and it is one the switch is closed.

An integer code to the topological system configuration for each load label based on a predecessor vector [26]; this representation indicates for each node its predecessor, in other words, the nearer node from which receives the feeding.

Initialization
A random initial population is considered. Parameters of GA must be initialized such as generation size, population size, crossover probability and mutation probability for capacitor addition and feeder reconfiguration.

Fitness Evaluation
All individual are evaluated with the same fitness function. The fitness function incorporates the objective function, i.e., the total costs associated to power losses, energy losses and capacitors equation (1) with cost penalties if a individual violates any of the constraints. The fitness function, f_k, can be expressed as follows:

$$f_k = C_k + \alpha \cdot \Delta V_k + \beta \cdot \Delta I_k \qquad (5)$$

Where:

C_k : Total cost of individual k (equation 1)
α : Voltage penalty factor
β : Current penalty factor
ΔV_k : Voltage constraints
ΔI_k : Currents constraints

A significant value (over 10000) is given to α, β penalty factors if the associated voltage or current constraint is violated, this makes the objective function more away from the undesirable solution.

Reproduction operation
In this operation, the matting pool needs to be formed by the population in proportion to their elitism. Elite ones will copy more to the matting pool. The roulette wheel selection was used to guarantee the occupancy of an area equal to the individual's share of the total fitness.

Crossover
Given a switched and capacitor crossover probability, a crossover is performed considering one or more crossover point.

Mutation
Given a switched and capacitor crossover probability, random alteration of genes in an individual may occur. A switches mutation represents a simple bit change; a capacitor mutation represents a change in bus number to any valid location or the reactive power setting.

TEST RESULTS

The proposed method was implemented in the C programming language on a Pentium III 550MHz, to demonstrate its performance two system benchmarks was considered for this paper: first a 16 bus IEEE system used to validate the proposed GA methodology with other references [25] and a 733 bus practical distribution system used to test the algorithm efficiency on a practical distribution network [26].

16 bus IEEE test system

This is a frequently studied IEEE distribution system obtained from [15] and displayed in Figure 3. The system consists of 16 buses, three feeders, 13 sectionalizing switches and three tie switches. This system is used in this paper with two purposes, in the first place to validate the proposed method and in second place to show the advantage of the proposed GA method.
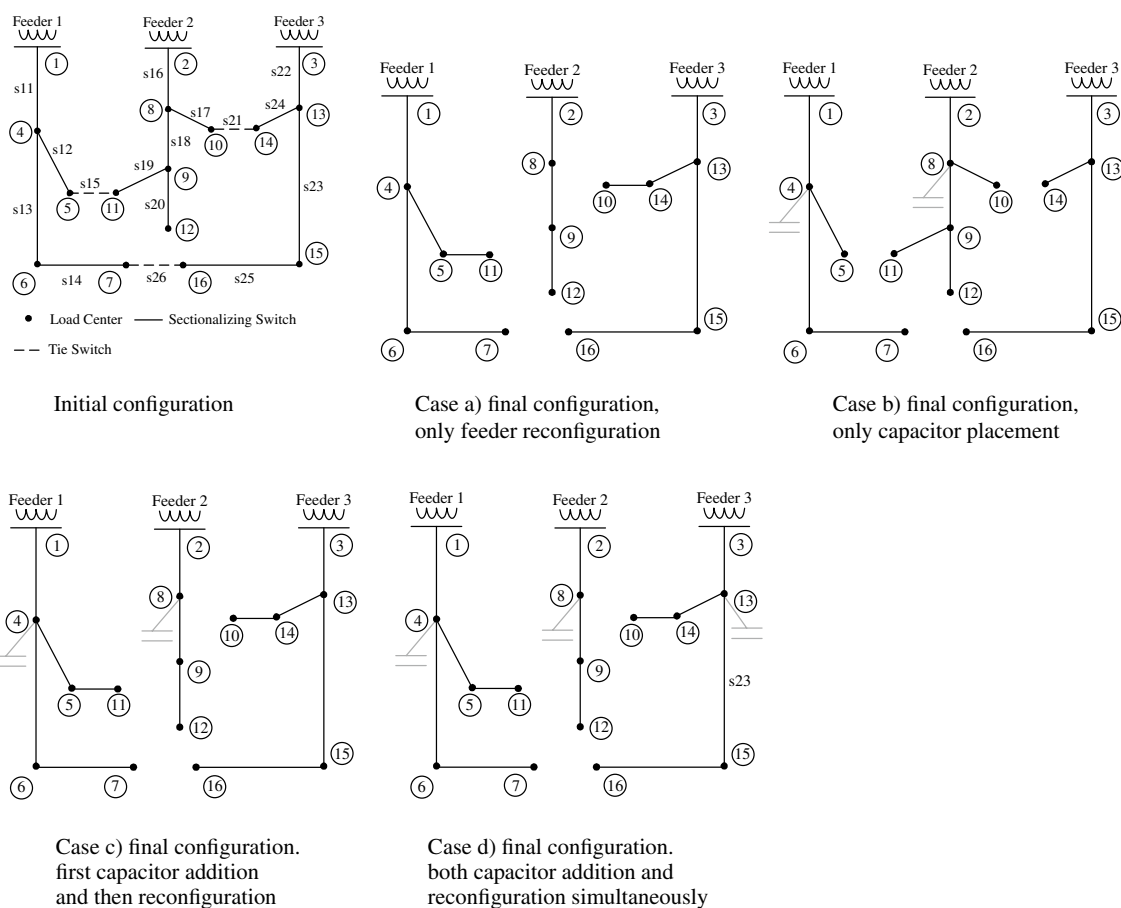

Initial configuration

Case a) final configuration, only feeder reconfiguration

Case b) final configuration, only capacitor placement

Case c) final configuration. first capacitor addition and then reconfiguration

Case d) final configuration. both capacitor addition and reconfiguration simultaneously

Figure 3. Final system configurations for the 16 bus IEEE system, case 1.

Case 1
Simulation results are presented for the 16 bus IEEE system and compared to the feeder reconfiguration and capacitor setting obtained from [25], which use simulated annealing (SA) to solve the problem, both feeder reconfiguration and setting of capacitor are taken into account together, but only power losses reduction is considered.

The system load is assumed to be constant and buses 4, 8 and 13 are selected to set up capacitor banks for feeder 1, 2 and 3, respectively. Practical size available for the capacitor banks are 300, 600, 900, 1200, 1500 and 1800 kVAr. In order to compare results, this paper has considered the same four cases presented by Su [25]. These four cases are the following:

Case a: Only feeder reconfiguration is considered.

Case b: Only capacitor addition is considered.

Case c: Both capacitor addition and feeder reconfiguration are considered; however, capacitor addition is carried out before feeder reconfiguration.

Case d: Both capacitor addition and feeder reconfiguration are considering and are taken into account simultaneously.

The genetic parameters setting considered for all simulation cases are show in Table 2, the initial population is randomly determined according to the system size and crossover rate according to typical value for GA algorithm.

The final system configuration for the four cases studied are depicted in Figure 3 and summarized in Table 3.

Taken into account both capacitor setting and feeder reconfiguration simultaneously can generate more power losses reduction than considering them separately, such as Figure 4 shows.

Table 2. Genetic parameters setting. Case 1.

Genetic Parameter	Setting
Initial population size	100
Preserved population size	50
Switches mutation rate [%]	0.01
Capacitor mutation rate [%]	0.01
Crossover rate [%]	20
Crossover point rate for capacitor [%]	35
Crossover point rate for switches [%]	7

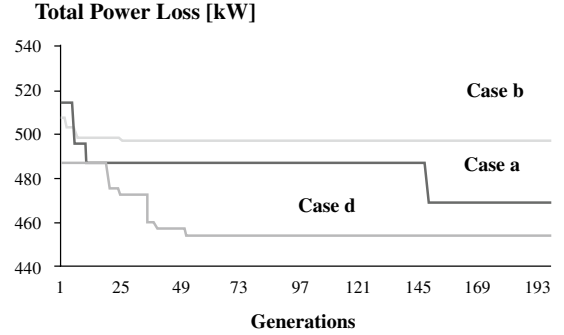**Total Power Loss [kW]**

Figure 4. Genetic algorithm performance for the case 1.

The obtained results are the same as [25] presents and validate the proposed methodology. Table 3 show that case d) can reduce power loss the most among these four cases.

Case 2

It is important to point out that the approaches proposed in this paper minimize the total costs, considering active power and energy losses, and fixed or switched capacitor placement. However, the reference [25] only minimizes active power losses with only fixed capacitors.

Then to show some of the advantages and simulation alternatives of the proposed approach the 16 bus IEEE system was studied with the following considerations:

• Three load level were considered with the load duration data (T=one year) for the system presented in Table 4.

Table 3. Results for the four cases studied on the 16 bus IEEE system, case 1.

Main items	Original configuration	Case a	Case b	Case c	Case d
Switches status alternated	—	{15,19}, {21,17}	—	{15,19},{21,17}	{15,19}, {21,17}
Maximum bus voltage	1	1	1	1	1
Minimum bus voltage	0.96927	0.971575	0.97132	0.97362	0.97362
Capacitors added [Kvar]:					
Bus 4	—	—	1800	1800	1800
Bus 8	—	—	1800	1800	1800
Bus 13			0	0	900
Total power loss [MW]	0.5144	0.4691	0.4971	0.4552	0.4543
Power loss reduction [%]	—	8.81	3.37	11.51	11.69

Table 4. Load duration data. Case 2.

	level 0	level 1	level 2
Load level (p.u.)	1.1	0.6	0.3
Time interval (hours)	1000	6760	1000

- Voltage and current constraints were considered: Vmax =1.1 pu., Vmin = 0.9 pu., Imin = 0.18 pu.
- Instead of minimizing only power losses, the costs of capacitor and power-energy losses were considered too. The cost constants assumed for this problem according to equation (2), (3) are the following:Kp=300US$/ kW/year, Ke=0.1 US$/kWh and Kc=5 US$/kVAr.
- The same switched and capacitors from the case 1 were considered, but now they can be located in any bus of the system.

Under these conditions the same four cases were analyzed. A costs comparison results are presented in Table 5 and the detail for the case d is summarized in Table 6.

From Table 5 it can be observed that the best solution corresponded to case d), with both feeder reconfiguration and capacitor setting are taken into account simultaneously.

733 bus test system
To analyze a large-scale distribution system a quite efficient string representation model was developed and a balanced distribution system modeling was employed, with comprehensive modeling of diverse components such as distribution lines, core losses in transformers, loads represented by diverse voltage dependent models and fixed or switched capacitors.

Table 5. Costs comparison for a 16 bus IEEE system, case 2.

Main items	Initial configuration	Case a	Case b	Case c	Case d
Max total power loss [MW]	0.6316	0.5988	0.5764	0.5574	0.5513
Total Cost loss [US$]	388427	377669	353230	354591	345352
Cost loss reduction [%]	—	2.8	9.1	8.7	11.1

Table 6. Final results for 16 bus IEEE system, case 2.
Considering both capacitor addition and reconfiguration simultaneously.

Main items	Load level 0	Load level 1	Level 2
Switches status alternated	{17,21} {19,15}	{17,21} {19,15}	{14,26} {17,21} {19,15}
Maximum bus voltage	1.000	1.000	1.002
Minimum bus voltage	0.972	0.988	0.998
Capacitors added [Kvar]			
Bus 8	1800	0	0
Bus 7	1500	300	0
Bus 9	1200	0	0
Total power loss [MW]	0.5513	0.1700	0.0759

Table 7. Cost comparison for a practical 733-bus distribution system.

	Initial configuration	Only capacitor placement	Only feeder reconfiguration	Both capacitor placement and reconfiguration simultaneously
Max. power loss [KW]	737	677	654	601
Total loss cost [US$]	100011	97334	89141	88866
Loss cost reduction [%]	—	2.7%	10.9%	11.2%

The method has been applied to a practical distribution system. It is a three-phase balance network, 13.8 kV, with 733 buses, 118 switches and 754 laterals.

Time variation of load is also involved, using annual load duration data, Table 8. Details of the data of this example system can be found in [26].

Table 8.   Annual load duration data for 733 buses system.

	level 0	level 1	level 2	level 3
Load level (p.u.)	1.03	0.894	0.771	0.589
Time interval (hrs.)	2160	2160	2160	2160

Voltage and current constraints were considered: Vmax =1.15 pu., Vmin = 0.85 pu., Imin = 0.18 pu.

A variable switched capacitor bank with four labels 150, 300, 450, 600 kVAr was assumed and a maximum of 4 new capacitor is considered. The capacitors cost function is given in equation (6)

$$C(Q) = 810 \text{ US\$} + 1.5 \text{ US\$/KvAr }(Q) \qquad (6)$$

Instead of minimizing only power losses, energy and peak load loss reduction, and capacitor cost are considered in the cost function. The cost constants assumed for this problem according to equation (2), (3) are the following: $Kp=0,01938$ US\$/kWh, $Ke=9.1$ US\$/kW/year. Table 9 summarize the genetics parameters.

Test results confirm that the proposed approach can efficiently search the optimal or near-optimal solution for energy and power loss cost minimization considering feeder reconfiguration and capacitor placement.

Table 9.   Genetics parameters for 733 buses test system.

Genetic Parameter	Setting value
Initial population	1000
Evolution population	400
Maximum iterations	4000
Switch mutation rate (%)	0.005
Capacitor mutation rate (%)	0.001
Crossover rate (%)	20
Switch crossover point (%)	20
Fixed capacitor crossover point	20
Capacitor placement crossover point (%)	20
Capacitor size crossover point	20
Penalty voltage factor (US\$/V)	15000
Penalty current factor (US\$/V)	15000

In addition, it can be seen from Table 7 that simultaneously taking into account both feeder reconfiguration and capacitor placement is more effective than using only one technique. The genetic algorithm performance in this case is shows in Figure 5.
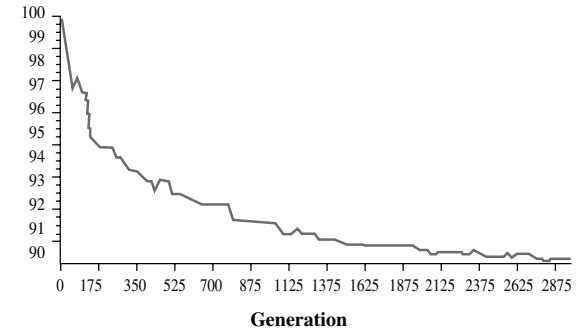
Total Lost Cost [US\$]

Figure 5. Genetic algorithm performance for a 733 buses test system.

CONCLUSIONS

In this paper a genetic algorithm (GA) is proposed for loss cost minimum optimization in distribution systems. The approach has been tested in many networks and the test results lead to the following conclusions:

- Taken into account both capacitor setting and feeder reconfiguration simultaneously can generate around 10% more energy-power losses reduction than considering them separately.

- An efficient coding system was developed for applying GA to the target problem; it handles possible generation of strings with violation of operational constraints, so that the proposed approach has a high efficiency in power-energy cost loss reduction.

- As size of the network and the load levels considered increase, the simultaneous solution requires more computational time than the separately solution (only reconfiguration or only capacitor setting).

- A detailed distribution network modeling is employed, it include loads represented by diverse voltage dependent models, load duration curve, fixed and switched capacitor, sectionalising and tie switches, transformer losses, fixed and variable capacitors costs. For this reason the result presented in this paper shown that the proposed approach has better response than other methods and is suitable for application to large-scale practical distribution systems.

REFERENCES

[1] J.J. Grainger and S.H. Lee. "Capacity release by shunt capacitor placement on distribution feeders: a new voltage-dependent model". IEEE Trans. Power App. Syst. Vol. PAS-101, Issue 5, pp. 1236-1244. May 1982.

[2] M.E. Baran and F.F. Wu. "Optimal sizing of capacitors placed on a radial distribution system". IEEE Trans. Power Delivery. Vol. 4 Nº 1, pp. 735-743. January 1989.

[3] H.D. Chiang, J.C. Wang, O. Cockings and H.D. Shin. "Optimal capacitor placement in distribution systems. Part I: A new formulation and the overall problem". IEEE Trans. Power Delivery. Vol. 5 Nº 2, pp. 634-642. April 1990.

[4] S. Sundhararajan and A. Pahwa. "Optimal selection of capacitors for radial distributions systems using a genetic algorithm". IEEE Trans. Power System. Vol. 9 Nº 3, pp. 1499-1507. August 1994.

[5] Y.C. Huang, H.T. Yang and C.L. Huang. "Solving the capacitor placement problem in a radial distribution system using tabu search approach". IEEE Trans. Power System. Vol. 11 Nº 4, pp. 1868-1873. November 1996.

[6] L.L. Lai and J.T. Ma. "Application of evolutionary programming to reactive power planning-comparison with nonlinear programming approach". IEEE Trans. Power System. Vol. 12 Nº 1, pp. 198-204. 1997.

[7] K.Y. Lee and F.F. Yang. "Optimal reactive power planning using evolutionary algorithms: a comparative study for evolutionary programming, evolutionary strategy, genetic algorithm and linear programming". IEEE Trans. Power System. Vol. 13 Nº 1, pp. 101-108. 1998.

[8] G. Levitin, A. Kalyuzhny, A. Shenkman and M. Chertkov. "Optimal capacitor allocation in distribution systems using a genetic algorithm and a fast energy loss computation technique". IEEE Trans. Power Delivery. Vol. 15 Nº 2, pp. 623-628. April 2000.

[9] R.A. Gallego, A.J. Monticelli and R. Romero. "Optimal capacitor placement in radial distribution networks". IEEE Trans. Power System. Vol. 16 Nº 4, pp. 630-637. November 2001.

[10] M.A.S. Masoum, A. Jafarian, M. Ladjevardi, E.F. Fuchs and W.M. Grady. "Fuzzy approach for optimal placement and sizing of capacitor banks in the presence of harmonics". IEEE Trans. Power Delivery. Vol. 19, pp. 822-829. April 2004.

[11] J.P. Chiou, C.F. Chang and C.T. Su. "Ant direction hybrid differential evolution for solving large capacitor placement problems". IEEE Trans. Power System. Vol. 19 Nº 4, pp. 1794-1800. November 2004.

[12] M.R. Haghifam and O.P. Malik. "Genetic algorithm-based approach for fixed and switchable capacitors placement in distribution systems with uncertainty and time varying loads". IET-Generation, Transmission and Distribution. Vol. 1, Issue 2, pp. 244-252. March 2007.

[13] I.C. da Silva, S. Carneiro, E.J. de Oliveira, J. de Souza Costa, J.L.R. Pereira and P.A.N. Garcia. "A Heuristic Constructive Algorithm for Capacitor Placement on Distribution Systems". IEEE Trans. Power System. Vol. 23 Nº 4, pp. 1619-1626. November 2008.

[14] A. Merlin and H. Back. "Search for a minimal loss operating spanning tree configuration for an urban power distribution system". Proc. of the 5th Power System Conference (PSCC), pp. 1-18. Cambridge. 1975.

[15] S. Civanlar, J.J. Grainger, H. Yin and S.S.H. Lee. "Distribution feeder reconfiguration for loss reduction". IEE Trans. Power Delivery. Vol. 3 Nº 3, pp. 1217-1222. July 1988.

[16] D. Shirmohammadi and H.W. Hong. "Reconfiguration of electric distribution networks for resistive line losses reduction". IEEE Trans. on Power Delivery. Vol. 4 Nº 4. April 1989.

[17] K. Nara, A. Shiose, M. Kitagawoa and T. Ishihara. "Implementation of genetic algorithm for distribution system loss minimum reconfiguration". IEEE Trans. Power System. Vol. 7 Nº 3, pp. 1044-1051. August 1992.

[18] H.C. Cheng and C.C. Kou. "Network reconfiguration in distribution systems using simulated annealing". Electric Power System Research. Vol. 29, Issue 3, pp. 227-238. 1994.

[19] G.P. Peponis, M.P. Papadopoulos and N.D. Hatziargyriou. "Distribution network reconfiguration to minimize resistive line losses". IEEE Trans. Power Delivery. Vol. 10 Nº 3, pp. 1338-1342. July 1995.

[20] H. Rudnick, I. Harnisch and R. Sanhueza. "Reconfiguration of electric distribution systems". Revista de la Facultad de Ingeniería-Universidad de Tarapacá. Vol. 4. Arica, Chile. 1997.

[21] Y.T. Hsiao and C.Y. Chien. "Multiobjective optimal feeder reconfiguration". IEE Proc. Gener. Transm. Distrib. Vol. 148 Nº 4, pp. 333-338. July 2001.

[22] J.P. Chiou, C.F. Chang and C.T. Su. "Variable scaling hybrid differential evolution for solving network reconfiguration of distribution systems".

IEEE Trans. Power System. Vol. 20 Nº 2, pp. 668-674. May 2005.

[23] E.M. Carreno, R. Romero and A. Padilha. "An Efficient Codification to Solve Distribution Network Reconfiguration for Loss Reduction Problem". IEEE Trans. Power System. Vol. 23 Nº 4, pp. 1542-1551. November 2008.

[24] D. Jiang and R. Baldick. "Optimal electric distribution system switch reconfiguration and capacitor control". IEEE Trans. Power System. Vol. 11 Nº 2, pp. 890-897. May 1996.

[25] C.T. Su and C.S. Lee. "Feeder reconfiguration and capacitor setting for loss reduction of distribution systems". Electric Power System Research. Vol. 58 Nº 2, pp. 97-102. 2001.

[26] R. Olivares. "Reconfiguración y localización óptima de condensadores en redes de distribución". Tesis para optar al título de Ingeniero Eléctrico. Departamento de Electrónica. Universidad de Tarapacá. Arica, Chile. 2001.

[27] Z. Rong, P. Xiyuan, H. Jinliang and S. Xinfu. "Reconfiguration and capacitor placement for loss reduction of distribution system". TENCON '02 Proceedings. 2002 IEEE Region 10 Conference on Computers, Communications, Control and Power Engineering. Vol. 3, pp. 1945-1949. October 28-31, 2002.

[28] M. Kalantar, Rahman Dashti and Reza Dashti. "Combination of Network Reconfiguration and Capacitor Placement for Loss Reduction in Distribution System with Based Genetic Algorithm". In Proc. 41st International Universities Power Engineering Conference, UPEC2006. Vol. 1, pp. 308-312. September 6-8, 2006.

[29] Z. Dong, F. Zhengcai, Y. Du and Z. Liuchun. "Capacitor switching and network reconfiguration for loss reduction in distribution system". IEEE Power Engineering Society General Meeting, pp. 1-6. Montreal, Canada. December 2006.

[30] D. Zhang, Z. Fu and L. Zhang. "Joint Optimization for Power Loss Reduction in Distribution Systems". IEEE Trans. Power System. Vol. 23 Nº 1, pp. 161-169. 2008.

[31] Chung-Fu Chang. "Reconfiguration and Capacitor Placement for Loss Reduction of Distribution Systems by Ant Colony Search Algorithm". IEEE Trans. Power System. Vol. 23 Nº 4, pp. 161-169. 2008.