DEMONSTRATING AN EFFICIENT CAPACITOR LOCATION AND SIZING METHOD FOR DISTRIBUTION SYSTEMS - APPLICATION TO THE MACAU NETWORK

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RESUMO
Este artigo apresenta a aplicação à rede de Macau de um novo método de localização optimizada de baterias de condensadores e respectivo dimensionamento, incluindo esquemas de controlo de escalões, com os objectivos de minimização de perdas na rede, de investimentos nos sistemas de compensação e de manutenção de nível de tensão nos barramentos do sistema dentro de uma gama adequada. A nova técnica, desenvolvida no INESC, recorre a uma metodologia de Algoritmos Genéticos. O exemplo apresentado é ilustrativo do interesse e potencialidades do novo método, que tem uma aplicação muito geral.

ABSTRACT
This report presents the application to Macau network of a new method for the optimized location and sizing of capacitor banks, including tap control schemes, meeting the objectives of power losses and investment minimization, as well as keeping node voltage within adequate bands. The new technique, developed at INESC, makes use of Genetic algorithms. The paper includes an example that illustrates the interest and potential of the new method, which has a very wide application.

1. INTRODUCTION

The reactive power (VAR) planning problem is one important problem in power system. The issues of the problem are to determine (1) the most adequate locations to install capacitors, (2) the types and sizes of capacitors to be installed, (3) the setting of capacitors at different loading conditions such that the capacitor cost in conjunction with energy loss are minimized while load conditions and operational constraints are met. This capacitor placement planning problem was solved based on Genetic Algorithms, which have several advantages over traditional methods employed to solve the same problem.

The optimal capacitor placement planning can be easily formulated as multi-objective, constrained optimization problem if Genetic Algorithms are employed. Since Genetic Algorithms are based on 0-1 coding technique, they can deal with the discrete nature of capacitor units very naturally. In the study presented in the following paragraphs, the problem was simplified so that it treated only normal operation and did not consider contingency cases.

2. PROBLEM FORMULATION

The comprehensive formulation of optimal capacitor placement planning problem as a constrained, non-differentiable, multi-objective optimization problem is given as follows. Three objective functions used in the study are discussed. The first one addresses the cost associated with capacitor placement (i.e. purchase, installation and maintenance). The second one is related to cost for energy losses and the third one is related to voltage profile.

Cost function:
Cost function includes cost of capacitor placement and cost of total energy and power losses in a distribution system. In the study, cost for both fixed and switchable types are considered.

Cost of fixed capacitors

The cost of fixed capacitors is associated with cost of installation and purchase of capacitor banks. Mathematically, it can be given as follows:

$$C_F(u) = \sum_{k \in N_C} C_k(u_k^0)$$
$$= C_c(N_A) + \sum_{k \in N_c, u_k^0 \neq 0} C_I(u_k^0)$$

where

u_k^0	: The size of capacitor at bus k during peak load level
$C_c(\cdot)$	: The fixed installation and maintenance cost
$C_I(\cdot)$	: The cost of capacitor banks
N_c	: The number of candidate buses
N_A	: The number of bus where capacitors are added
k	: The index of bus number

Cost of switchable capacitors

The cost of installing switchable capacitors can be represented by Cs(u). This cost function depends on the relative values of the k-th bus capacitor control setting u_k^i (where u_k^i is the control setting of the k-th bus capacitor during i-th load level). If u_k^i are equal for all i, it means only fixed capacitors are needed to install at bus k and this portion of cost can be set to zero. Thus the total cost of capacitor can be represented by

$$C_{cap}(u) = C_F(u) + C_S(u)$$

Cost of energy and power losses

One of the objectives of the problem is to minimize the total real power losses arising from transmission lines, which can be calculated as follows:

$$P_{loss} = \sum_{k=1}^{N_l} G_{k(i,j)} \left[V_{ii}^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j) \right]$$

where

N_l	: Total transmission lines on the system
$G_{k(i,j)}$	: Conductance of transmission line k connected between bus i an j
V_i	: Voltage magnitude at bus i
δ_i	: Voltage angle at bus i

and can be directly obtained after load flow results. Now, let P_{Loss}^i represent total real power loss in the distribution system during i-th load level and T_i be the time duration of i-th load level. Then, total energy loss of the distribution system is written as

$$E_{loss}(x,u) = \sum_{i \in N_T} T_i \cdot P_{Loss}^i(x,u)$$

where

N_T	: Total number of load levels to be studied

The cost of energy losses can be calculated by multiplying the total energy loss by a dollar-to-kWh conversion factor K_E.

$$C_{e.Loss}(x,u) = K_E \cdot E_{Loss}(x,u)$$

Here, factor K_E may reflect a capitalized value of the kW of losses, if necessary. In practice, it must reflect the marginal cost of energy generation.

There is another effect of losses with is the marginal gain in capacity of the power system, as a result of reactive compensation. This gain must reflect marginal investment costs both at generation and at transmission level (lines, transformers).

In our model this is calculated as a function of the maximum value of P_{Loss}^{i} obtained for a given configuration, at the peak value of the load curve. If marginal investment values are known (at least an estimation of these), then the following expression may be added to the costs incurred due to the existence of power losses:

$$C_{p.loss}(x,u) = \sum_{i \in N_G} K_{p.i} \cdot P_{Loss}^{o}(x,u)$$

where

$P_{Loss}^{o}(x,u)$ - Losses at peak hour

$K_{p.i}$ - Marginal investment cost coefficients for the generation and transmission system

N_G - Number of different marginal costs to be considered; for instance, for generation, for substation transformers and for transmission lines.

Deviation of voltage:
Bus voltage is an important index for security and it prompts us to use the following deviation function (deviation of bus voltage from a specified voltage) as one of the objectives function to the problem in order to force bus voltage magnitude to approach specified voltage magnitude V^{spec}. V^{spec} is normally set to unity.

$$C_{dv} = \sum_{k=1}^{N_b} \left(\frac{\left| V_k - V_k^{spec} \right|}{\Delta V_k^{max}} \right)^2$$

where

N_b : Total buses of the system under study
V_k : Voltage magnitude at bus k
V_k^{spec} : Specified voltage magnitude at bus k
ΔV_k^{max} : Maximum allowable voltage deviation limit at bus k

Overall problem formulation:
The objective of the overall problem is to

$$\textbf{\textit{Min}} \qquad C(x,u) = C_{cap}(u) + C_{e.Loss}(x,u) + C_{p.Loss}(x,u) + k \cdot C_{dv}(x)$$

subject to

(1) Load constraints:

The load constraints are the real and reactive power balance described by a set of power flow equations which can be expressed in compact form

$$F(x,u) = 0$$

(2) Operational constraints on bus voltage:

$$V_{min} \le V_k \le V^{max} \qquad k = 1,2,3,\ldots,N_b$$

(3) Constraint on fixed capacitors:

$$u_k^i = u_k^0 \le m_c u_s, \qquad \text{for all } k \in N_c, i \in N_T$$

where

m_c : maximum number of capacitor banks to be installed at bus k
u_s : standard capacitor size of one bank

(4) Constraint on switchable capacitors

$$u_k^i \le u_k^0 \le m_c u \qquad \text{for all } k \in N_c, i \in N_T$$

It should be pointed out that if more information about active and reactive production limits of generators are provided, the operational constraints such as

$$P_{gj}^{min} \le P_{gj} \le P_{gj}^{max} \qquad j = 1,2,\dots,n_g$$
$$Q_{gj}^{min} \le Q_{gj} \le Q_{gj}^{max} \qquad j = 1,2,\dots,n_g$$

can also be included without major difficulties.

3. SOLUTION TECHNIQUE

The problem of optimal capacitor placement and control in a distribution system belongs to a class of combinatorial optimization problems. Generally speaking, these problems are solved by heuristic approaches or approximate techniques. In the study, a Genetic Algorithm has been applied to solve the problem because it has the following attractive features:

(1) it is capable of finding global optimal solutions,

(2) it can handle different kinds of constraints such as equality, inequality, differentiable and non-differentiable constraints quite easily,

(3) it is easy to treat in it the number of capacitor units as discrete variables.

The only disadvantage of this optimization technique is that it might take considerable amount of computation time to achieve a (near) global optimal solution, if an advanced model and care in its development are not adopted.

Coding technique

When Genetic Algorithms are applied to optimal capacitor placement problem, a string consisting of binary numbers represents the number of capacitor banks in each node of the network. When standard size capacitor banks are provided, the size of capacitors installed in each node can be determined by multiplying the number of capacitor banks with this standard size. Because it is not important for the main topic discussed here, we have omitted the decoding technique used in the study. An additional restriction is used to limit the capacitor size to be installed to some maximum size.

Fitness function

In the method developed at INESC, the weighted summation of three objectives functions (power loss, investment cost and voltage deviation) is used as fitness function to evaluate the performance and the constraints might be treated as penalty functions and added to the fitness function. It should be pointed out that a feasible solution can be obtained with Genetic Algorithms quickly, but it is a somewhat impractical solution because the installations at adjacent nodes are small most of time. Hence, a constraint limiting the number of the capacitor was added by using a suitable penalty term to the above fitness function, so the resulting fitness function can be represented as follows:

Fitness function = M - objective function - penalty function

where

$g(o)$ = Objective function

$$= sf_1\left[\sum_{k=1}^{N_c} C_k(u_k^0)\right] + sf_2\left[K_E \sum_{i=0}^{N_T} T_i \cdot P_{Loss}^i\right] + sf_3\left[\sum_{i=0}^{N_T}\sum_{l=1}^{N_b}\left(\frac{V_l^i - V_l^{spec}}{V_l^{spec}}\right)^2\right]$$

$p(o)$ = Penalty function

$$= sf_4 \cdot N_p$$

sf_1, sf_2, sf_3, sf_4 = Scaling factors that scale the contribution of each term

N_p = Number of bus constrained to install capacitor banks during peak load level

Note that we didn't include in this expression the marginal investment cost dependent on losses $C_{p.Loss}$, for the sake of simplicity, but this is not a limitation on the method, as it is evident.

Algorithm

For each generation, do the following steps:

1. Generate a new configuration by decoding the chromosome.

2. For each load level i=0,1,2,...,N_T with i=0 as peak load level and i≠0 off peak load level, do the next step, where the control setting at each load level is determined.

3. Find capacitor control settings:

(i) Decode the chromosome representing the size of capacitors being installed to candidate buses and the control setting at peak load is upper limit.

(ii) Run a balanced load flow to check the feasibility. Check the voltage magnitude at all PV and PQ buses for each load level. If any is violated, return the fitness function with the number of buses violating the voltage constraints, i.e.

$$f(o) = sf_5 \cdot \sum_{i=0}^{n_t} \sum_{k=1}^{n} \left(\left| V_k^i - V_k^{spec} \right| \right)$$

if no voltage magnitude constraints are violated, go to next step.

(iii) Calculate the real power loss, cost for purchase, installation and maintenance of installed capacitor unit to each of several adjacent nodes and this makes the total cost increase due to installation cost. A constraint limiting the number of capacitors installed is included in the fitness function to lead the algorithm to install capacitors at fewer nodes and reduce the installation cost. The fitness function to evaluate the total performance are returned.

4. Finish all generations? If not, return to step (1), otherwise proceed to next step.

5. Print out the optimal configuration.

The output of the above solution algorithm gives the optimal capacitor size vector $(u_1, u_2, \ldots, u_{N_c})$, here $u_k = \left(u_k^1, u_k^2, \ldots u_k^{N_T}\right)$ and u_k^j is the control setting of bus k at load level j. This piece of information can be used to determine the number, location, sizes of either fixed or switchable capacitors to be placed. The types of capacitors to be installed at bus k can be determined by control setting u_k, using the following rule:

if $u_k^1 = u_k^2 = \ldots = u_k^{N_T}$, then a fixed type of capacitor is to be installed at bus k, otherwise a switchable type of capacitor is to be installed at bus k.

For the purpose of illustration, a 3-node distribution system will be used. Suppose the output of the solution algorithm gives the following control setting vector:

$$u = \begin{Bmatrix} \{3 & 5 & 0\} \\ \{3 & 4 & 0\} \\ \{3 & 2 & 0\} \end{Bmatrix}$$

This indicates that three banks of fixed capacitors are needed to be installed on node 1 for all load levels, and five banks of switchable capacitors are needed to be placed on node 2 (a fixed base of 2, with 3 more switchable) and no capacitor is needed at node 3.

4. A TEST ON THE MACAU C.E.M. NETWORK

The proposed solution algorithm has been implemented in C language under UNIX operation environment. A test system has been built based on the real 12-node, Macau distribution network, operated by CEM - Companhia de Electricidade de Macau. The one-line diagram is shown in the Appendix.

It must be stressed that this is, in fact, a *test system*, although based on a real system; therefore, the conclusions extracted from the study presented below cannot be extrapolated to the actual situation of the network in Macau, nor used to evaluate it. However, as a didactic example, it benefits form having to consider all the aspects of a real system with actual reactive power compensation needs.

System impedances, transformers and generators tap ratios used were the ones of Macau network. In all cases studied, the following specifications and data are used.

Maximum voltage limit V_{max}	***Minimum voltage limit*** V_{min}	***One bank***
1.025 p.u.	0.975 p.u.	3 MVar

Varying loads are taken into account in the solution algorithm and all load data are referred to those recorded in July, 1994 in Macau. In the simulation study, three load levels are considered. They are referred to as peak, normal and off-peak load level. The planning period is one month in the simulation and it can be prolonged to a larger period. The time duration for normal load level is longer than the other load levels and may reflect the approximation to the fluctuation of load demands over one month. The corresponding time duration are:

	Peak	***Normal***	***Off-peak***
Duration (h)	186	372	186

An initial load flow study was done for peak, normal and off-peak load level without any capacitor in the network. From the voltage magnitudes and the given voltage limits, we can select the buses at which the capacitors can be installed, i.e. “Candidate buses”. The voltages at generator buses (PV and Ref. buses) are assumed to remain constant. In order to simulate the low voltage problem occurring in the system, voltage magnitudes at buses 2 and 3 are set to 0.975 p.u. for peak load. In this case, all buses are selected as candidate buses except PV, Ref. buses and bus 12, because these buses have no low voltage problem.

$$\text{Candidate bus} = \{4,5,6,7,8,9,10,11\}$$

Because eight buses are considered and each bus needs 4 bits to represent the size of capacitor to be installed, the length of the chromosome in the case is

$$\text{Size} = 4\times8\times3 = 96 \text{ bits}$$

Case 1:

Since the control parameters, such as population size, crossover probability and mutation probability, are very important when Genetic Algorithms are applied, these parameters must be determined with some care. In the case, various values for these parameters were studied and the following data was used:

Cost of capacitors used in case 1

Type of capacitor	**Capital cost**	**Installation & maintenance**
Switchable	\$400 / bank	\$1000
Fixed	\$900 / bank	\$450

Five separate runs were made to test the efficiency and accuracy using different control parameters for the algorithm. In 30 runs, the probability of resulting 13.8K capacitor cost (\$10.8K for purchasing new capacitors and \$3K for installation and maintenance) is 63.3% and this is the lowest found capacitor cost up to present.

These outcomes resulting in less energy loss cost under different populations and mutations are shown in Table 1. The fifth and sixth rows show the energy loss without and with capacitors during one month and the seventh row shows the energy saving due to installed capacitor. Table 2 shows the reactive power injection for results in column one and three.

From Table 1, we can see that the energy loss saving is $1.6612K in column 3 and it is the highest energy saving over all runs, but it requires installing more capacitors in the distribution system. It shows an obvious trade-off phenomena between capacitor cost and energy saving. The system planner can make the decision depending on the planned period, i.e. if the planning period is long, energy loss cost can be treated as a key factor in decision making because the capacitor is one-time transaction cost while the energy loss saving lasts.

Table 1 Best five outcomes with respect to energy saving during one month

Population	**30**		**25**		**20**	
Solution	***A***	***B***	***C***	***D***	***E***	***F***
Mutation	0.005	0.003	0.005	0.003	0.005	0.003
Cap. cost	$13.8K	$13.8K	$16.0K	$13.8K	$13.8K	$13.8K
Energy loss without Cap.	$782.64 $\times$31 = $24.26K	$782.64 $\times$31 = $24.26K	$782.64 $\times$31 = $24.26K	$782.64 $\times$31 = $24.26K	$782.64 $\times$31 = $24.26K	$782.64 $\times$31 = $24.26K
Energy loss with Cap.	$729.20 $\times$31 = $22.61K	$733.66 $\times$31 = $22.74K	$729.05 $\times$31 = $22.60K	$732.50 $\times$31 = $22.71K	$731.15 $\times$31 = $22.67K	$731.26 $\times$31 = $22.67K
Energy saving	***$1.675K***	***$1.518K***	***$1.661K***	***$1.554K***	***$1.596K***	***$1.593K***
Bus	4{9,5,0} 7{9,9,1} 9{9,9,0}	7{9,7,1} 9{9,7,0} 11{9,9,}	4{3,3,0} 7{9,9,1} 8{9,9,0} 11{9,3,0}	5{9,6,0} 8{9,9,1} 9{9,9,0}	4{9,9,0} 7{9,9,0} 9{9,6,1}	7{9,9,0} 9{9,9,1} 11{9,6,0}

Table 2 The reactive power injection for the solution A and C

	Solution A			**Solution C**			
Bus	4	7	9	4	7	8	11
Peak	26.4927	26.2942	26.3008	8.8630	26.4283	26.4379	26.5261
Normal	15.0322	26.8636	26.8694	9.0284	26.9078	26.9137	8.9930
Off-peak	0	2.9877	0	0	2.9877	0	0

Also, the results suggested by the algorithm were to install only switchable type of capacitors. It happened because in these examples the costs for capacitors were fictitious and the capital cost for switchable type resulted much less expensive than that of fixed type. Because this is just an essay, it is meaningless to draw any conclusion about whether or not fixed type capacitor installation yields better voltage regulation, loss minimization and lower investment. Conclusively, solution A suggested to install at each of nodes 4, 7 and 9 a capacitor bank of 27 Mvar (with taps at nodes 4 and 7 at least).

Case 2:

In the case, another set of capacitor costs was used to study the same problem. Since the population of 30 and mutation probability 0.005 turned out to be more efficient in case 1, the same set of control parameters were applied in this new case. The four best solutions with respect to energy saving are shown in Table 3, and the capacitor cost now is shown as follows:

Cost of capacitor used in case 2

Type of capacitor	**Capital cost**	**Installation & maintenance**
Switchable	$1200 / bank	$1000
Fixed	$900 / bank	$450

Table 3 Four best outcomes with respect to energy saving during one month

Solution	**A**	**B**	**C**	**D**
Cap. cost	$16.45K	$18.55K	$16.45K	$15.25K
Energy loss without Cap.	$782.64 × 31 = $24.262K	$782.64 × 31 = $24.262K	$782.64 × 31 = $24.262K	$782.64 × 31 = $24.262K
Energy loss with Cap.	$740.84 × 31 = $22.966K	$742.10 × 31 = $23.005K	$742.57 × 31 = $23.020K	$742.65 × 31 = $23.022K
Energy saving	***$1.296K***	***$1.257K***	***$1.242K***	***$1.240K***
Bus	7{6,6,6} 9{8,8,0}	7{7,7,7} 9{9,9,0}	7{8,8,0} 9{6,6,6}	7{6,6,6} 9{7,7,0}

<u>Some observations:</u>

- Although the capital as well as installation and maintenance of switchable capacitor are more expensive than that of fixed type, the switchable capacitor installation yields better voltage regulation and loss minimization when systems are subject to load changes.
- It also indicates that capacitors installed at Bus 7 and 9 are more advantageous.

For a visual inspection, Figure 1 shows the real power loss before and after capacitor installation at three different load levels for the results listed in column one (solution A). Figures 2 and 3 show the voltage magnitudes at different extremes of the load levels.

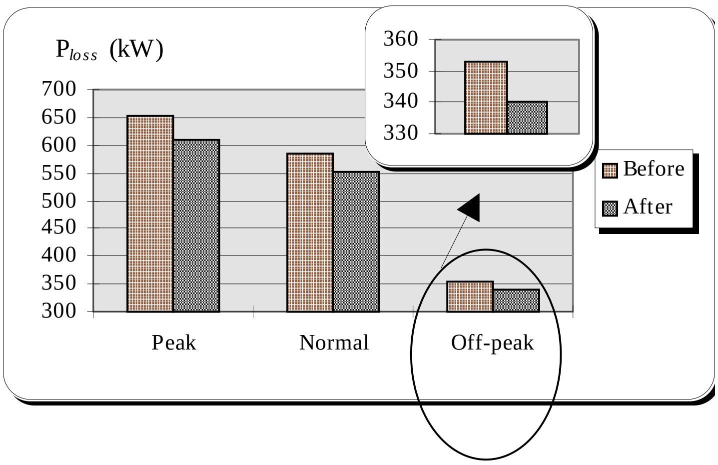

Fig. 1 Power loss at three different load levels in case of before and after capacitor installation

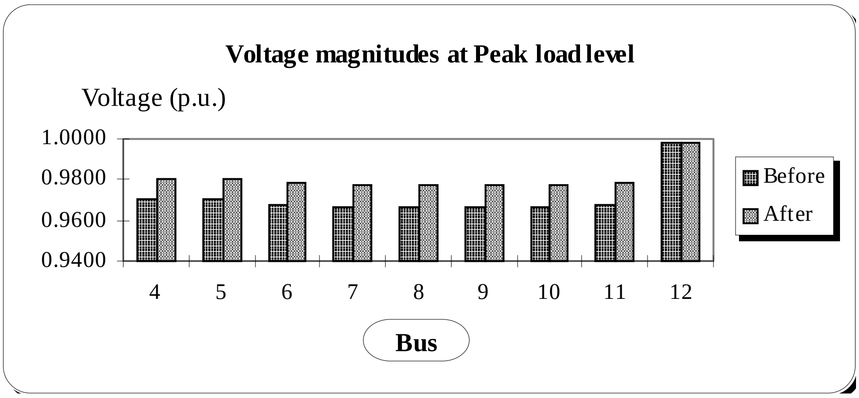

Fig. 2 Voltage profiles at Peak load level in case of before and after capacitor installation

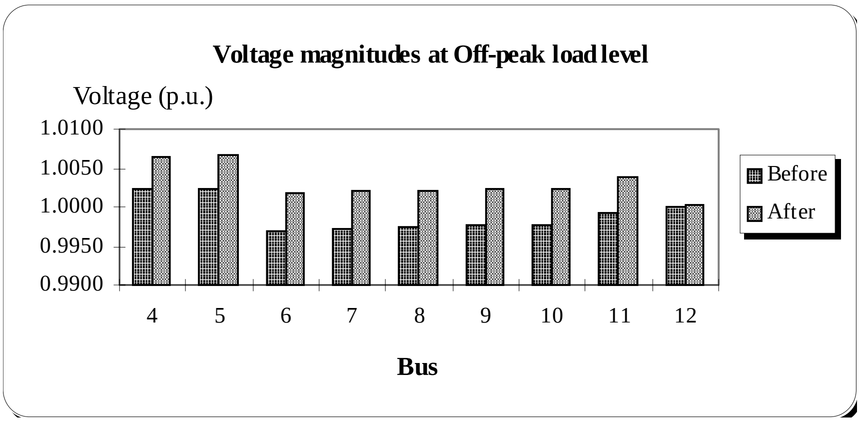

Fig. 3 Voltage profiles at Off-peak load level in case of before and after capacitor installation

5. CONCLUSION

This paper illustrates how the optimal capacitor placement was solved based on a powerful optimization method - Genetic Algorithms. Both fixed or switchable capacitor were considered, demonstrating the flexibility of the modeling possible.

Of course, including capacitors in a power system would require that other types of studies should be performed, namely about possible ressonance with harmonic frequencies at some load levels or system configurations, and also thier contribution to the dynamic stability maintenance of the system. These types of studies, presently, are made *after* some scenarios about sizing and location of capacitors have been set: it is still not possible, today, to integrate everything in the same model.

Two cases are studied in the paper. From the simulation results, the existence of a trade-off decision between investment (capacitor cost) and economy (power flow loss) for the optimization problem becomes evident. System planner must deal with these conflicting objectives with great care.

Because of some simplifications or assumptions (generator tapping at bus 2 and 3 are purposely set to 0.985 in order to simulate the low voltage problem, it might not be the real operational condition existed in Macau system in July, 1994) made in the formulation of problem, a comparison between the simulation results generated by the proposed algorithm and the physical reality of Macau distribution system cannot be made.

In any case, there is one difference between the real network in Macau and the example cases presented, which deserves a comment. In the C.E.M. system, the existing configuration of capacitor installation is that capacitors are installed at all PQ load buses only; however, the best solution found in the algorithm at Case 1 suggested to install capacitors at bus 4 (SEKH) where no local load exists. This should teach us all a lesson, that sometimes the best solution (which is always a compromise among many factors) is not the obvious one - that's certainly a reason to use some advanced techniques to deal with the problems…

In case 2, switchable capacitor installation at the system is demonstrated, resulting in better voltage regulation and loss minimization, subject to load changes, and the best solution suggested to install capacitor at two buses only (Bus 7 and 9).

The new algorithm, developed at INESC and based on Genetic Algorithms is capable of finding robust, reliable solutions for system planners; we recall that, for a real case study, the following factors must be taken in account:

- A comprehensive modeling of system components (Generators and Transformers),
- An enough accurate load modeling,
- Precise (as possible) information about the capital as well as installation and maintenance costs of both fixed and switchable type capacitor,
- Site conditions (such as the space available to install capacitors) when considering candidate buses in the problem. Their restriction or consideration may result in more costly investment (since the problem is more confined), but it may reflect better the physical realities.
- Information about load growth and network planned expansion. This will allow to establish a dynamic policy on the investment in capacitor, taking into account future scenarios and not only a static load profile.

The model developed at INESC is able to take in account all these aspects and also qualitative rules that an utility may wish to consider, conditioning the search of a solution. The Power System INESC team is also available to offer consultancy or cooperation other partners, besides C.E.M., of Macau, in relation to the VAR planning problem - in fact, a new project in now being conducted together with ELECTRA, from Cabo Verde, on a similar subject, which has a known important economic relevancy .

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