Identification of Operation Strategies of Distribution Networks Using a Simulated Annealing Approach

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Abstract - In this paper we present a model to identify optimal operation strategies of electric distribution networks considering that one wants to minimize active power losses. This objective can be achieved by adequately selecting transformers taps and sections of capacitor banks that are in operation. In order to turn the model more realistic the developed application admits the specification of admissible voltage ranges for each node and maximum branch currents for each line and transformer. The integer nature of this problem virtually turned it impossible to be solved for real sized networks given its combinatorial nature, its complexity and thus the involved calculation time. In this paper we describe the use of a meta-heuristic - Simulated Annealing - to this problem in order to address the difficulties just referred. The use of the developed application will be illustrated using a IEEE test network and a realistic network having 645 nodes based on a Portuguese distribution system.

Keywords: Loss Minimization, Volt/VAr Control, Simulated Annealing, DMS.

I. INTRODUCTION

The operation of distribution networks turned more and more relevant in recent years given that it is at this level that more serious problems affecting the quality of service usually occur and that one aims at operating them with good economic and efficient indices. From this point of view, the identification of optimal operation strategies considering the minimization of active losses is becoming more and more important together with obtaining good voltage magnitude profiles. The operation of these networks is strongly determined by the topology of the system in operation, by the position of transformer taps and by the sections of capacitor banks in operation. These issues are directly related with several aspects associated with the technical operation conditions of the network and with the service quality offered to the clients. Among them one can refer

- in the first place, the descentralized generation of reactive power is an important resource leading to the reduction of reactive branch flows. This enables a more efficient use of transmission lines since they can be more intensively used to transmit active power without violating thermal ratings;
- secondly, the previous aspect can still be responsible for the postponement of new investments. This issue clearly has a new relevance with the advent of dispersed generation connected to distribution networks and with the implementation of market mechanisms in the electric industry;
- thirdly, the identification of the position of transformer taps and sections of capacitor banks can be performed considering a number of constraints not to be violated. Among them, constraints imposing admissible ranges for nodal voltage magnitudes and constraints related to thermal branch flow limits are surely important ones. The integration of the first type of constraints can be interpreted as a way to specify admissible deviations for voltage magnitudes, that is, maximum values for voltage drops. This way, the integration of these constraints is an effective way of contributing to guarantee increased service quality levels.

The literature on this area describes several models aiming at optimizing the operation conditions of distribution networks. For instance, in papers [1] to [5] one can find descriptions of models and algorithms aiming at identifying optimal reconfiguration strategies - *switching* actions - of distribution networks. In this sense, reconfiguration is understood as a resource that distribution companies can use in order to improve both their economic and technical performances. On the other hand, papers [6] to [9] describe algorithms aiming at selecting the most adequate position of transformer taps and number of sections of capacitor banks in operation considering that one wants to minimize active losses. These approaches assume that the topology of the network in operation is fixed.

The increasing investments directed to the distribution sector, namely required by the higher quality standards impose in the scope of the move to electricity markets, enable that an higher number of equipments are telecommanded. This is also related to the implementation of automation function in Distribution Control Centres and with the increased number of real time measures available on those centres. These new capacities together with the possibility to treat dimensionally larger problems, as the typically related to distribution networks, are imposing the upgrade of the traditional SCADA systems to new systems aiming at supporting and aiding at real time the operation activities conducted in those centres. The installation of Distribution Management Systems in distribution networks means that several concepts and techniques already available in transmission systems are migrating to the

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distribution sector. The research reported in this paper can be exactly integrated in this line area since we aim at developing new applications, in some cases, or adapting already existing ones so that they can efficiently answer to the problems emerging in distribution networks.

In this paper we report the application of the Simulated Annealing technique [10] to [12] to the above described problem considering that the topology of the network is fixed. This approach has several advantages related to the possibility of considering the integer nature of several variables of the problem and also with the integration in the algorithm of several steps aiming at avoiding local optima.

Apart from this introductory section, Section II includes a brief description of some theoretical concepts of the Simulated Annealing technique and Section III presents the formulation of the problem and several details related with the practical implementation of that technique. Section IV includes results for two networks:

- the IEEE 24 node/36 branch test system. This network was conveniently adapted in order to integrate 5 transformers having each one 11 taps. In this case, the Simulated Annealing based solution is compared with the global optimal solution identified by enumeration of all possible configurations;
- a real sized network based on a Portuguese distribution system. This network has 4 transformers having each one 21 taps, 1 transformer with 19 taps and 4 capacitor banks each one with two possible positions;

Finally, apart from several comments on the results obtained for those networks, Section V includes some conclusions.

II. THE SIMULATED ANNEALING PROCESS

A. Introduction

Real sized combinatorial problems are difficult to be solved for real time purposes. This is the main reason why the use of meta-heuristic procedures often consists on a fair compromise between the quality of solutions and the required computation time.

In the 1980's new contributions to deal with combinatorial problems started to emerge: genetic algorithms, neural networks, tabu-search and simulated annealing. In this scope, the concept of annealing in combinatorial optimization was introduced by Kirkpatrick, Gelatt Jr. and Vecchi (1983) and independently by Cerny (1985).

Simulated annealing (SA) appears like a flexible meta-heuristic that is an adequate tool to solve a great number of combinatorial problems. SA consists on a simple framework that takes advantage of relaxing optimality in a transitory way in order to escape from local minimum. It is based on an iterative heuristic improvement together with a control mechanism that allows solutions to escape from local optima. The flexibility and simplicity of this framework turn this meta-heuristic adequate to model particular and, often, complex constraints, providing solutions in acceptable computation time.

SA bases on the Metropolis method that allows, with a certain probability, movements towards worse solutions. Basically, the Metropolis process consists on two steps. In the first one the temperature is raised to a state of maximum energy while in the second step the temperature is slowly lowered till a minimum energy state, equivalent to the thermal equilibrium, is reached.

B. Analogy between combinatorial and thermodynamic process

In order to more clearly explain the SA algorithm, we will present an analogy between a combinatorial problem and physical systems integrating a large number of particles. In this scope, we will use a SA strategy to deal with the identification of an operation point of a distribution network in order to conduct an analogy analysis with the Metropolis method related with a physical process). This analogy can be stated as follows:

- the **alternative solutions or configurations** of the combinatorial operation distribution problem are equivalent to the physical system **states;**
- the network configuration (alternative solutions) **attributes** are equivalent to the **energy** of different states;
- the **control parameter** is equivalent to the **temperature parameter**. This parameter can be set so that about half the new configurations analysed are accepted at the start of the process.

The evolution of the solution algorithm is simulated using probabilistic sampling techniques supported by successive generation of states. This process begins with an initial state evaluated by an energy function f_i. After generating and analysing a second state - energy f_j - it is performed an acceptation test. The acceptance of this new solution depends on a probability computed with (1).

$$P_c(\text{accept } j) = \begin{cases} 1 & \text{if } f_k(j) \le f_k(i) \\ e^{\frac{(f_k(i) - f_k(j))}{c}} & \text{if } f_k(j) \ge f_k(i) \end{cases} \qquad (1)$$

$c \in \Re^+$

$c = k_B.T$

k_B Boltzman constant

T Temperature

In order to use this algorithm, some basic decisions will have to be taken regarding these parameters. In Table I we present some indications regarding the analogy with the physical process and in the next subsection we will present some additional elements to direct the setting of these parameters.

Table I - Keystroke Decisions For Process Convergence

General (temperature lowering)	Problem Specifications
T_0 (initial temperature)	i_0 (initial solution)
L_k (iteration number)	Neighbourhood generation
T_k (temperature function)	Evaluation of solutions.
Stop criteria	

C. General Decisions

The SA cooling process integrates a number of data regarding the initial value, the decrement function, the number of iterations for each temperature level and the freezing temperature scheme.

The temperature or control parameter (T_0) should be large enough to prevent the algorithm from being captured by local optimum points. On the other hand, the temperature should not be that high that it could lead to excessive computation time. In purely planning problems, the computation time issue may not be so relevant since we frequently do not need solutions in real time.

The choice of the initial control parameter was performed so that about half the configurations were accepted in the beginning of the process. The setting of this parameter is strongly depends on the nature of the problem. In any case, expression (2) can be used to obtain the value of this parameter.

$$T_0 = -\Delta C_i / \ln(0.5) \tag{2}$$

In this expression:

- T_0 is the initial temperature parameter
- ΔC_i is the cost difference between solution *i* and solution *i-1*

The number of iterations per temperature level can also be interpreted as the time during which a constant temperature is maintained. This number is chosen taking into account experiences from reported in the literature. This value can be easily obtained from initial temperature calculations where the possible neighbours must be explored. This number is highly dependent on the problem size and the desired accuracy.

Two temperature schedules or cooling schemes can be used in order to lower the temperature. The first one corresponds to a stepwise temperature reduction scheme while the second adopts a continuous temperature reduction process. Previous experiences on this area indicate that the quality of results do not benefit from adopting the continuous reduction scheme. On the other hand, the computation time is smaller when using a geometric schedule. The above reasoning justified the adoption of the first referred process to direct the cooling scheme, according to (3).

$$T_i = \beta^i T_0 \tag{3}$$

In this expression, T_i is the temperature parameter during period i and β^i is the temperature decreasing parameter in period *i*.

An average value for β was also defined. From our experience we derived a value between 0.85 and 0.92. Larger values would yield high computation times, and smaller values, below 0.85, typically lead to poorer quality solutions.

The freezing point of the problem or the stopping point of the algorithm is determined so that, for a given temperature level, the number of worse accepted solutions is inferior than a pre-specified value.

D. Specific Problem Decisions

The initial solution of the algorithm can be identified using some auxiliary algorithm. Specifically, in the problem we are addressing, the initial solution can be simple corresponding to a situation where all transformer taps and capacitor banks are at a default position. This position can, for instance, be derived from the information available in DMS database or can correspond to the central tap available in each transformer and to completely disconnect all capacitor banks.

This solution is evaluated by running a power flow exercise. From this analysis one gets the values of branch losses, voltage magnitudes and branch currents that, apart from other variables, are relevant to the characterization of this operation point.

Afterwards, it is generated a neighbourhood structure that will be used to direct the move from the current solution to the next one. In our particular problem, the neighbourhood solution simple consists of increasing or decreasing one step the value of transformer taps or sections of capacitor banks. The selection of a new solution is performed using a probabilistic sampling method that selects one decision variable to be altered - that is one transformer tap or section of capacitor bank. For the selected one, the sampling process should also indicate if the step is to be increased or decreased.

III. FORMULATION OF THE PROBLEM

The minimization problem of active power losses can be formulated by (4) to (9).

$$\min z = \sum_{nr} g_{ij}.(V_i^2 + V_j^2 - 2.V_i.V_j.\cos\theta_{ij}) \tag{4}$$

subj. $$h(V,\theta,t_f,e_c) = 0 \tag{5}$$

$$V^{min} \le V \le V^{max} \quad \text{for each node} \tag{6}$$

$$\left|\underline{I}_{ij}\right| \le \left|\underline{I}_{ij}\right|^{max} \quad \text{for each line} \tag{7}$$

$$t_f \in \{t_{f1}, t_{f2}, t_{f3}, ...\} \quad \text{for each transformer with taps} \tag{8}$$

$$e_c \in \{e_{c1}, e_{c2}, e_{c3}, ...\} \quad \text{for each cap. bank} \tag{9}$$

In this formulation:

- $h()$ represents the AC power flow equations;
- t_f stands for the available values of transformer taps;
- e_c represents the available reactive powers of capacitor banks;
- V and θ are the voltage magnitudes and phases;
- g_{ij} corresponds to the conductance of branch ij;
- $|I_{ij}|$ is the current magnitude flowing in branch ij.

Traditionally, this problem has been solved assuming that transformer taps and that the sections of capacitor banks are represented by continuous variables. Such formulation consists of a non-linear optimization problem which can be solved using, for instance, gradient based methods. The solution obtained this way must be approximated to the closest discrete solution. This strategy presents several drawbacks. On one hand the gradient method can converge to local optima. On the other hand, as the original problem is an integer one we cannot be sure that the final integer solution coincides with the global optimum one.

The application presented in this paper uses Simulated Annealing to identify a strategy to minimize active power losses. According to the description presented in section II, in the next paragraphs we will detail the adopted algorithm:

i) the initial solution corresponds to the actual operation position for transformer taps and capacitor sections, if available, or to default positions;

ii) the initial solution is considered as actual ($x^{current}$) and set as present optimal solution identified as x*. For the current configuration (solution) a power flow study is run. This power flow study has the purpose of evaluating global power losses, node voltage magnitudes and line current flows;

iii) each solution is evaluated by the so-called evaluation function, $F(x^{current})$. In our case, expression (10) was adopted for F.

$$\begin{aligned} F(x) = \; & \text{ActiveLosses} + \\ & + \sum_{\text{for each bus}} (Vmag_i - V_i^{max}).f_1(Vmag_i) + \\ & + \sum_{\text{for each bus}} (V_i^{min} - Vmag_i).f_2(Vmag_i) + \\ & + \sum_{\text{for each branch}} \left(\frac{I_i - I_i^{max}}{I_i^{max}} \right) f_3(I_i) \end{aligned} \quad (10)$$

Functions f_1, f_2 and f_3 are given by (11) to (13).

$$f_1(Vmag_i) = \begin{cases} 0 & \text{, if } Vmag_i \le V_i^{max} \\ \text{ActiveLosses} & \text{, if } Vmag_i > V_i^{max} \end{cases} \quad (11)$$

$$f_2(Vmag_i) = \begin{cases} 0 & \text{, if } Vmag_i \ge V_i^{min} \\ \text{ActiveLosses} & \text{, if } Vmag_i < V_i^{min} \end{cases} \quad (12)$$

$$f_3(I_i) = \begin{cases} 0 & \text{, if } I_i \le I_i^{max} \\ \text{ActiveLosses} & \text{, if } I_i > I_i^{max} \end{cases} \quad (13)$$

assign $F(x^{current})$ to F(x*);
initialise iteration counter n at 1;
initialise iteration worst solution than current one counter, CountWorse, at 0;
initialise Temperature parameter at 1.0;

iv) Build the neighbourhood of present solution considering all the possible combinations of transformer taps and capacitor sections that differ from current one of one unit. Select a configuration randomly within the neighbourhood of present solution (x_n);

v) Run a new power flow study for the present configuration x_n and evaluate this solution by using (10). This leads to $F(x_n)$;

vi) Refresh the information related with the present solution according to:

if $F(x_n) \le F(x^*)$ then
    set x_n to x* and to $x^{current}$;
    set CountWorse at 0;
else
    increment CountWorse;
    select a random number p in [0.0;1.0];
    evaluate p(level s) computing:

$$p(\text{level s}) = \exp\left(\frac{F(x^{current}) - F(x_n)}{0.00025 \times \text{temperature}} \right) \quad (14)$$

    if $p \le p(\text{level s})$ then
        assign x_n to $x^{current}$;

vii) if CountWorse > maximum iteration number without improvements then go to ix);

viii) if n > maximum iteration number for a temperature level then
    assign temperature = temperature lowering schedule x temperature;
    if temperature < final temperature then
        go to ix);
    set n at 1;
else increment n by 1;
go to iv);

ix) end.

According to this algorithm each solution is evaluated using (10) that integrates four terms. The first one corresponds to the branch active losses as computed by the power flow run. The remaining three terms correspond to penalty functions included whenever there are violations of the specified range of voltage magnitudes or if the maximum current branch flow are exceeded. It should be referred that in this expression the values of voltage magnitudes and branch currents are expressed in p.u.

IV. CASE STUDY

A. IEEE 24 nodes/36 branches network test

In this sub-section we will present the results obtained for the IEEE 24 nodes/36 branches. The complete data for this network can be found in reference [13]. This network is includes by 31 lines and 5 transformers. The tests that were conducted using this network considered 11 taps in each transformer. Each tap corresponds to a 0.01 increment within the interval [0.95,1.05]. Initially, the transformer taps were considered at the nominal values (position 6 equivalent to 1 p.u.). Loads were set to the values referred in [13] multiplied by a factor of 1.8. The initial value for the acceptance function was 139112.49.

The selected Simulated Annealing parameters are:

- the number of iterations for the same temperature level is 25;
- the initial temperature level was set to 1.0. The lowering step determining the cooling scheme (parameter β in expression 3) is 95% of previous temperature;
- the maximum number of iterations without improvement of the evaluation function is set to 75;

With these parameters the algorithm converged in 312 iterations and the temperature was reduced till 0.54. The final value for the acceptance function was 137916.45. The improvement of the evaluation function value regarding the initial value was 1196.04.

In Figure 1 we present the evolution, along the search process, of the actual evaluation function value (continuous line) and for the best solution found till the current iteration (dotted line).

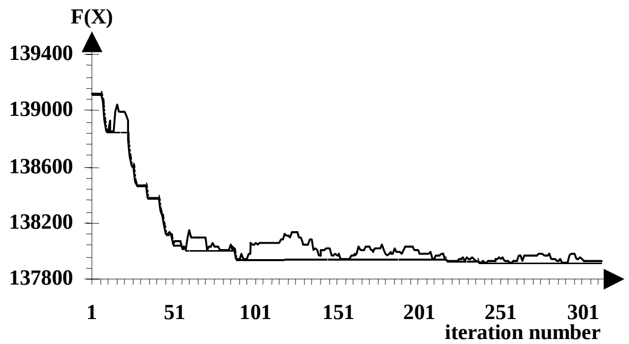

Fig. 1 – Evolution of the evaluation function for the current solution (continuous line) and for the best-identified solution (dotted line) for the 24 node network.

B. Network based on a Portuguese distribution system

In this subsection we will present the results obtained for a Portuguese base distribution network. The network has 645 nodes, 4 transformers, each one with 21 taps in the primary level and with a voltage range within [0.85,1.15] p.u. and a step of 0.015, one transformer with 19 taps in the secondary level and with a voltage range within [0.85,1.15] p.u. and a step of 0.0167. The initial position for the transformers taps was the nominal one (position 11 and 10 respectively corresponding to the value 1.0). We also considered 4 capacitors with two possible positions (on or off). In the initial solution capacitors were considered on. The initial acceptance function value was 825.83.

The Simulated Annealing parameters were set to:

- the number of iterations for the same temperature level is 45;
- the initial temperature level was set to 1.0. The lowering step determining the cooling scheme (parameter β in expression 3) is to 95% of previous temperature;
- the maximum number of iterations without improvement of the evaluation function is set to 135;

With these parameters the algorithm converged in 256 iterations and the temperature lowered till 0.77. The final value for the acceptance function was 741.19. This represents an improvement of the evaluation function of 84.64 regarding the initial value.

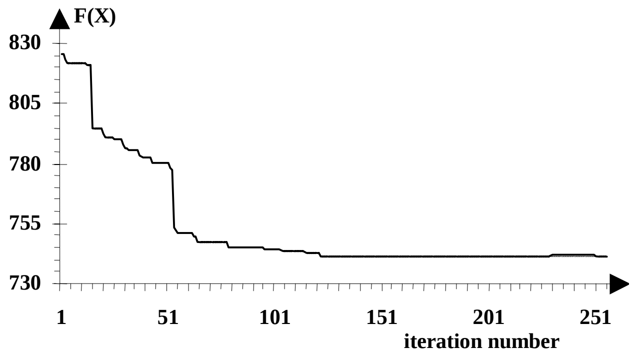

Fig. 2 – Evolution of the evaluation function for the current solution (continuous line) and for the best identified solution (dotted line) for the 645 node network.

Figure 2 presents the evolution, along the search process, of the current value of the evaluation function (continuous line) and for the best identified solution found till the current iteration (dotted line). In this graphical representation the two previously referred lines almost coincide. This is due to the need to adequately scale the graph in order to fit in 1 column representation. In fact, the current solution suffered 143 changes along the whole iterative process while the best-identified solution was only changed 38 times.

C. Comments

Aiming at evaluating the algorithm performance in what concerns the efficiency of the search algorithm, we evaluated the 24 bus system considering all the possible combinations of the 5 transformer taps. As referred, this network has 5 transformers each one with 11 taps. This means that, in the scope of this enumeration process, 161051 power flow studies were run in order to analyse all possible configurations. As conclusions, we can refer that the best solution obtained with the enumeration process coincides with the best one identified using the *Simulated Annealing* approach. This aspect is even more remarkable if one compares the number of power flow runs. The SA required 312 versus 161051 for the enumeration process. Therefore, if the computation time of one power flow exercise is accepted as time unit, the SA approach only took 0.19% of the time required by the enumeration process.

For the real sized network, the dimension of the problem is already much larger given that it includes 4 transformers each one with 21 taps, 1 transformer with 19 taps and for on/off capacitor banks. This leads, if the enumeration process was to be considered, to a number of power flow runs of 59 122 224. If the time per power flow was 0.1 second this enumeration analysis would take as much as more than 2 months to be finished. The SA approach requires, as referred 256 iterations, although in this case we can not guarantee that the identified solution corresponds to the global optimum. Nevertheless, it corresponds to a good with a good trade-off between its quality and the required computation time.

V. CONCLUSIONS

In thsi paper we addressed a timely question in the scope of the optimized operation of distribution networks. As referred the identification of a good configuration to explore distribution networks is becoming more relevant given the integration of dispersed generation and the need to guarantee good service quality indices. These requirements, together with the move to market environments, are imposing new investments in distribution automation and in installing DMS systems.

In this sense methodologies as the one described can play an important role in order to achieve better both technical, economic and quality performance indices. The use of meta-heuristic schemes as the Simulated Annealing reported in this paper should be understood as an important contribution not only in demonstrating the feasibility of the application of these procedures but also as a way to clearly show the reduction in computational time. This, as it was demonstrated for the first example in the paper, can be obtained without compromising the quality of the results. Therefore, specially if real sized complex and combinatorial problems are to be addressed, Simulated Annealing techniques appear as specially interesting and displaying a good trade off between the quality of the solutions and the required computational time.

VI. ACKNOWLEDGMENT

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