Meta-heuristics Applied to Power Systems

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1 Introduction

This paper describes a number of real applications of meta-heuristics (in this case, Simulated Annealing) and Genetic Algorithms to Power System problems. The research work was developed in the framework of European projects and industrial contracts and addresses areas as: planning and operation of electrical distribution systems, wind park layout, unit commitment of isolated systems with renewable energy sources and voltage collapse in interconnected systems. The combinatorial nature comes naturally in Power Systems, since most of the decision variables are binary or integer due to technical reasons. On the other hand, a common characteristic to these problems is the presence of technical constraints, which poses difficulties to the application of meta-heuristics, leading to the need of penalty factors in the evaluation functions. The extended abstract also includes feature selection for security analysis using Artificial Neural Networks, a related topic, although not really an application of meta-heuristics. The abstract is organized as follows. Regarding each topic, the corresponding problem is briefly described, followed by the presentation of the approach and, in some cases, a summary of the results. Global conclusions and references complete the extended abstract.

2 Distribution systems planning

A main issue in planning electric distribution systems is to decide what new branches and injection points (substations) to construct. The decisions must be taken in order to meet future demand at minimum cost, without violating technical constraints (maximum current flow and maximum voltage drop). These networks are characterized by a great number of nodes and possible branches. The nodes are the injection points of the network, consumer points (loads), substations and generation from independent producers. The problem involves many integer-valued (0-1) variables related to the decisions to build or not build facilities. In addition, the overall problem is dynamic, since the decisions about investments must be made over a multi-period horizon. Besides investment cost, other criteria are generally considered (operating cost, reliability) and uncertainty is present due to forecasting.

In the Simulated Annealing strategy, the analogy between the electric distribution planning problem and the Metropolis algorithm can be stated as follows. The *alternative solutions or configurations* of the combinatorial electric distribution planning problem are equivalent to the physical system *states*. The network configurations (alternative solutions) attributes are equivalent to the different states' *energy*. The *control parameter*, which is such that about half the new configurations found are accepted at the start of the process, is equivalent to the *temperature parameter*. The SA cooling schedule integrates several aspects that are detailed in the next paragraphs:

- The choice of the initial temperature was such that about half the configurations were accepted;
- The number of iterations during which the temperature is kept constant was approximately 10 times the average number of possible neighbors. This value can be obtained from initial temperature calculations where the possible neighbors are explored;
- A stepwise temperature reduction scheme was used, with $T(i) = \frac{T(i-1)}{\beta}$
- From our experience an average value for b was derived between 0.85 and 0.92. Larger values yield high computation times, and smaller values, below 0.85, lead to poorer solutions.
- The freezing point is determined where the number of acceptances is very small. This point is highly dependent on the problem size and must be determined for each problem.

The initial solution is generated by an auxiliary algorithm that finds a shortest spanning tree, the weights used for the edges usually are the edges (branches) costs although other criteria could be used. A structure of neighborhood generation mechanism is then created. To eliminate a great number of trials only feasible solutions, S', from the solution space S are considered. This procedure consists of choosing all possible combinations of connected trees that result from removing a branch to the loop created by each edge of the co-tree entering the initial configuration. The alternatives are evaluated according to the criterion to be optimized.

A simulated annealing procedure was combined with the e-constraint search to form a methodology for solving the multiobjective planning problem. In practice the initial multiobjective problem was split into several single objective problems successively solved to generate non-dominated solutions. In [1] the detailed procedure to generate the set of efficient solutions is explained in detail.

3 Distribution systems operation - reconfiguration

Distribution networks are usually operated radially, but they have a meshed structure (with open lines) that allows several configurations. The reconfiguration of these networks by changing the switching devices status aims at optimizing the network configuration for a given load profile, by minimizing the power losses. A related problem is the service restoration problem in the sequence of a fault situation, when one tries to re-supply at least part of the loads. Besides the main objective of each problem (minimizing losses or minimizing load not supplied), the minimization of the total number of switching operations is also included as a criterion. In either case, the network reconfiguration is a multiobjective optimization problem. An algorithm to deal with this problem is detailed in [6]. The basic Simulated Annealing algorithm was used, with the following characteristics:

Initial solution When restoring service, the initial configuration represents the distribution network with the fault isolated and some consumers not supplied. When minimizing losses, the initial configuration is the present status of the network;

Neighborhood structure The neighborhood structure implemented depends on the problem. For the loss minimization problem when a branch is Opened another one is Closed, in such a way that the network remains radial and all the consumers remain served. For the service restoration problem, the rule is as follows: Close a branch that close no loops *or* Open any branch;

Evaluation function The evaluation includes a cost attribute (losses or power not supplied, depending on the problem) and penalties related to overload limits and maximum voltage drop. For the multiobjective case, a penalty is also included relative to the maximum number of switching operations allowed. Variation of this limit allows the generation of all the efficient solutions.

Results consist of a set of Pareto optimal solutions regarding the objectives. For instance, in a restoration situation, as the power not supplied decreases, the number of switching operations increases in different alternative schemes. The operator may then choose among the given set for the most satisfying solution, according to his preferences and temporary constraints not included in the model.

4 Distribution systems operation - reactive power control

In this section we present a model to identify optimal operation strategies of distribution networks considering that one wants to minimize active losses. This objective can be achieved by adequately selecting transformers taps and sections of capacitor banks that are in operation if one assumes that the topology in operation is fixed. In order to turn the model more realistic the application admits the specification of voltage ranges for nodes and maximum branch currents for branches.

The problem of minimizing active power losses can be formulated by (1) and (2) and technical constraints on voltage and current. 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 are the voltage magnitudes and gij corresponds to the conductance of 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, which may, or may not, be the optimal solution.

$$\text{Minimize } z = \sum_{nr} g_{ij} \cdot (V_i^2 + V_j^2 - 2 \cdot V_i \cdot V_j \cdot \cos\theta_{ij}) \quad (1)$$

$$\text{subject to } h(V, \theta, t_f, e_c) = 0 \quad (2)$$

The application detailed in [7] uses Simulated Annealing to identify a strategy to min. active power losses. In the next paragraphs are presented details of the adopted algorithm: the neighborhood of one solution, considering all the possible combinations of transformer taps and capacitor sections, includes all configurations that differ from the current one of one unit. The evaluation function integrates the active losses for the current configuration and terms representing penalty functions related to violations of the max. and min. voltage magnitudes in each node and the max. current flow in each branch.

To evaluate the algorithm performance concerning the efficiency of the search process, we simulated all possible combinations for the 5 transformer taps of a 24 bus system. This means that, in the scope of this enumeration process, 161051 power flow studies (as compared with 312 in our approach) were run in order to analyze 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 SA approach.

5 Wind park layout

In a wind park the location of wind generators is defined having in mind the wind and terrain characteristics. The internal electrical network of the wind park is a problem that involves the network topology determination and the definition of the cable sections to used. The solution of this problem can be obtained solving a global optimization problem that involves minimization of investments and minimization of operation costs. If reliability is taken into account in the design procedure, an evaluation of the interest on supplementary connections that provide alternative paths for the delivery of the energy is performed.

This optimization problem has combinatorial characteristics, due to the possibilities of connecting the several wind generators in the field and the type of discrete cable sections available [8]. The identification of solutions for the problem described was performed using a Genetic Algorithm that implements the concept of geographic isolation, based on a *nitching* scheme [5]. The chromosome is a string of bits, each bit having a binary value (0 or 1). In our problem this string has, for each generator, 8 bits that represent:

- L_1 to L_4 - type of connections in terms of topology (L_1 and L_3 are mandatory lines, L_2 and L_4 alternative lines, used for reliability purpose); W_{gui} - contains an information associated to situations where generator i is the last in the feeder; S_{eci} - 3 bits used to codify the section type of the cable to be used;

The length of each chromosome is therefore $8 \cdot n$, n being the number of wind generators in the park.

The fitness corresponds to the total cost, but it includes penalty terms related to the technical constraints, as shown in (7). In this expression nf is the number of feeders, ngu in the number of generators in the end of the feeder, L_{NC} is the number of lines not connected correctly, V_c and V_T are the number of violations of the voltage profile and of the thermal limits, C_C is the cost of cables (including protections), C_{JL} is the cost of energy losses, C_{ND} is the cost of energy not delivered to the grid, due to internal faults on the wind park, and $k1 \ldots k4$ are penalty factors.

$$FIT = k_1 \cdot nf + k_2 \cdot L_{NC} + k_3|ngu - nf| + k_4(V_T + V_C) + C_C + C_{JL} + C_{ND} \tag{3}$$

This approach was tested in the electrical design of some wind parks, namely in the case of a 10 MW wind farm with 20 wind generators, 500kW each. This corresponds to real wind park presently in operation in Portugal. In the GA approach, the values adopted for the crossover probability and the mutation probability were respectively 0.8 and 0.04, and the process was found to converge after 1500 generations. The solutions obtained are, for the tests performed, systematically better than the ones provided by the traditional engineering judgment and rules.

6 Preventive control procedure to avoid voltage collapse

Most power systems are nowadays operated close to their operating limits due to liberalization, increase in consumption, while economic and environmental constraints have limited construction of new generation facilities and lines. Therefore, it is important to evaluate the distance to voltage collapse and to identify preventive measures that avoid this voltage problem [4]. The model includes the possibility of modifying the current positions of transformer taps as well as the steps of capacitor banks or performing load shedding. It is obvious that load shedding is understood as an end of line resource, in the sense that it will only be used if there is no other way of supplying loads even changing transformer taps or capacitor steps. Most of the control measures (change in tap position, capacitor banks, feeders to be disconnected) correspond to discrete steps that lead to a combinatorial type problem.

The mathematical formulation of this problem corresponds to the optimization problem (4) to (6), and bounds on some variables. The objective function (4) integrates a term measuring the distance to voltage collapse (given by the total increase of load admitted by the system) and a second term μ assumes a sufficiently large value so that load shedding is used only if necessary. In this formulation, $f(X, u)$ represents the general equality constraints of the power flow problem, X is the state vector, u

is the vector of control variables.

$$\text{Maximize } C = Dist\_colp - \mu \cdot \sum P_{shed} \tag{4}$$

$$\text{subject to } f(X, u) = 0, \tag{5}$$

$$Dist\_colp \geqslant \epsilon \tag{6}$$

In order to avoid local minimum solutions, a deterministic crowding GA was used to solve the optimization problem described. The fitness function corresponds to the distance to collapse (in MVA) plus a penalty factor proportional to the summation of the load shed in each bus (MVA).

In order to evaluate the performance of the previously described approach we conducted several numerical tests considering the Reduced Mato Grosso system [3]. The results obtained were excellent in quality, matching with the ones obtained when the optimization problem in a continuous space was solved using the interior point method. When curtailment of loads was needed the approach adopted was able to provide better results than the traditional methods, due to the fact that it was dealing with the real specificity and characteristics of the amount of load supplied by each feeder in a substation.

7 Unit Commitment

The unit commitment problem is related to the hourly scheduling of the generators that will be running to satisfy the entire load, in a horizon of several hours (at least 48h). The problem is not separable in the intervals, since there are transition costs (due to start-up and shut-down costs) and constraints, and has been addressed traditionally by dynamic programming (small problems) and lagrangian relaxation.

The genetic algorithm used to solve the unit commitment problem is based on the general scheme of GA, but includes several enhancements. It replaces the standard selection scheme with a dedicated Niching Selection Scheme - Deterministic Crowding Selection. In addition, a dynamic mutation rate technique, Chromosome repair and Neighborhood digging schemes are also included, in order to accelerate convergence and enforce robustness. Encoding the chromosome plays an important role in the genetic algorithm. In the UC module, an efficient way is proposed to compress the length of the chromosome. The main idea comes from the observation that the generators will not switch on/off frequently and thus some of the variables can be reduced. With this method, the length of the chromosome can be reduced a lot. For example, in a problem with 17 generators and an hourly scheduling for 48 hours, the direct encoding will lead to 816 bits. On the other hand, if divide the 48 hours into 16 sections, the length of the chromosome will only be 368 bits.

The fitness function includes the generation and start-up and the shutdown costs of generators. To identify an infeasible chromosome a penalty cost is added when the schedule violates the constraints. To avoid trapping in local optima, dynamic mutation rate adjustment is used. Deterministic Crowding (DC) selection scheme is a niching method, which is used to preserve the diversity of the genetic algorithm. Chromosome repair is a corrective algorithm. The algorithm will correct slightly the infeasible chromosome, which is near the feasible region. Afterwards, the corrected chromosome will place it back to the population and enrich the genetic pool. Neighborhood digging concentrates mainly in feasible chromosomes. By searching the neighbor of the chromosome, the algorithm will find out some better chromosome to replace the original. By experience, we find that this genetic operator not only accelerates the convergence of the process, but also gives better results regarding both the economic optimization and the execution time, which was an important project constraint.

8 Feature Selection using ANN

Feature subset selection (FSS) is a central issue in a vast diversity of problems including classification, function approximation, machine learning and adaptive control. In this study, the selection of adequate variable subset is accomplished by sensitivity analysis of trained artificial neural networks (ANN). Data sets concern to power systems of islands of Crete, Greece and Madeira, Portugal. The problem under analysis refers to the dynamic security classification. This section describes how FSS and ANN tools may be used for enhancing classification performance. Results attained so far support the validity of the developed approach. The FSS methodology applied in [2] consists basically of three steps: (1) use of correlation analysis to discard linearly correlated features, (2) train an ANN with the remaining ones, compute sensitivities of its output (dynamic security index) with respect to all inputs and discard inputs with lowest sensitivity s_i indexes and (3) train a second ANN using only the remaining variables. Tests with a data set of the power system of Crete, initially with $N1 = 60$ attributes, lead to $N2 = 20$ after correlation analysis. An ANN was then trained and s_i calculus were performed, leading to further elimination of 14 variables. A new ANN was trained with the remaining $N3 = 6$ features. Performance was computed considering 22 attributes. The results were compared with the ones obtained with older approaches and the training and test errors were found to be smaller than before. Results show that some real data applications may be amazingly simplified without loss of performance.

9 Conclusions

Many Power System optimization or decision problems are of combinatorial nature, due to the intrinsic presence of integer and binary variables. The use of Simulated Annealing and Genetic Algorithms has proven to be successful even on difficult situations, related to real planning and operation problems. The examples shown are by no means complete, since many other applications exist, but are sufficient to demonstrate the practical interest of these methodologies to a demanding engineering field.

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