OPTIMIZING TOPOLOGY OF THE POWER DISTRIBUTION NETWORK USING GENETIC ALGORITHM

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Abstract: The article deals with application of genetic algorithm to the minimization of the operational cost of distribution network. The optimization is achieved by the change of the network topology or reconfiguration in terms of power network terminology. The optimization algorithm changes the setup of the switchgears to get such a configuration which leads to the minimum costs for power loss and minimum financial penalization for not delivering the electric power and therefore violating standards of the power supply continuity. The Finnish continuity standard at systems level and Portuguese continuity standard at single-customer level were selected for evaluation of the impact of power supply discontinuity and their impact is compared and discussed. The Genetic algorithm is designed as multi-attribute optimization with mono-objective evaluation using binary coding. Also since the optimization involves reconfiguration of the topology a simple solution to cope with invalid solution is described and discussed.

1 INTRODUCTION

During past decade, new challenges caused by the liberation process in electrical energy market of the European Union were introduced. While the liberation does not carry only new opportunities for the business but also new requirements given by state regulator, a way to minimize the risks of the penalization for the violation of the regulations was necessary to be found. The method of estimating these risks is well known and widely used and is based on the probabilistic model of the outages in the power network. Because the distribution companies are naturally monopolistic, the market in this area needs to be regulated by state. The task of the state regulator is to keep the requirements of customers, distribution company stockholders and power systems itself balanced. To cover the needs of customers and power systems the power quality standards were defined. One part of power quality standards is based on the monitoring of electrical energy supply continuity followed by costs evaluation of continuity violation. It enables the evaluation of network reliability and provides some clues about network's condition. It is also one of the tools to secure the investment to network by its owners. The electrical energy supply continuity is directly related to reliability of distribution network. The reliability improvement requires usually high investment to the networks' parts e.g. changing overhead lines by cables and so on. Therefore the distribution companies seek for cheaper solutions. The one of almost cost-free solution is a reconfiguration – changing the topology.

2 CURRENT DEVELOPEMENT

Using the reconfiguration of the power network to optimize the power network parameters started in middle 80's (Sarfi, 1996) but the main development took place in 90's of 20th century. The optimizations were mainly concern to decrease of power losses (Sarfi, 1996) or to balance power distribution (Baran, 1989) and heuristic method: Greedy search (Baran, 1989) or artificial intelligence: Genetic algorithms (Vitorino, 2009) or Swarm intelligence (Hosseini, 2008) were used. The power network

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reliability in connection with reconfiguration has been studied since 2003 (Brown, 2003). The main development in this field started in the beginning of the 21st century when liberalization of electric energy market was introduced in European Union (Hosseini, 2008), (Vitorino, 2009).

3 APPLICABLE NETWORKS

The electrical power networks are divided to transmission networks and distribution networks. The transmission networks create the central part of the system and are used for the transfer of the energy from the power plants or international connection points to the main points of consumption like big cities or important industry centres. These networks work on the voltage level up to 200 kV and usually operate as meshed networks. Between the transmission networks and end users, there are the distribution networks operating on variety of voltage levels from 110 kV (High voltage - HV) over 35 kV (middle voltage - MV) for industry to 400 V for low voltage (LV) customers. Each voltage level has its own properties and operated topology and it can be diverse in different countries and areas depended on historical and technical conditions. The article is based on the situation in the Czech Republic.

The transmission networks generally operate as a meshed network where reliability calculation is actually very complicated and where the reconfiguration operations are executed with different focus – primarily to the stability of the system. The networks on HV (110 kV) level in the Czech Republic do not contain sufficient number of reconfiguration points for proper optimization, on other hand the available data from the power networks on LV (0.4 kV) level do not currently provide enough information for practical evaluation. Power networks, fulfilling both requirements for optimization (enough data and possibility of effective reconfiguration), operate on MV (35kV and 22 kV) level. MV networks in Czech Republic are designed as meshed networks and they are operated as radial networks to enable simple dispatching control.

4 POWER NETWORK OPTIMIZATION

The optimization is based on four components– network topology reconfiguration, evaluation of the continuity standard, power losses calculation and quite basic version of genetic algorithm. The network reconfiguration is necessarily built-in the GA implementation.

4.1 Reconfiguration and Coding

Reconfiguration is a process of changing the topology of the power network using circuit breakers or section switches without disconnection of any end-point customer. The set of switches state (on/off) defines one solution (or a single individuum in terms of GA). Therefore the algorithm uses naturally binary coding system. Apart from 1 (switched on) and 0 (switched off) the third status (-1) is used for the situations when the status of the switch is unknown during the optimization. The -1 marker has to be used to distinguish a state when the change of the switch position may break any of set condition. This marker arises during the GA operators processing and practically means that the individual should be corrected so that it represents a viable solution (given only by a set of 0 or 1).

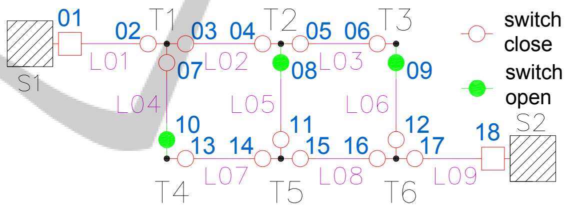

Figure 1: Model of the network.

The switch position in the chromosome (locus) is mapped to a single switch position in the network. The mapping is constant during the whole simulation. During the optimization, each valid individuum represents a valid set of switches state fulfilling the conditions of 1) all the customers being connected and 2) providing no loops (radiality condition). The way to achieve the reconfiguration from one set of switches to another is not taken into account during optimization and is considered to be practically possible.

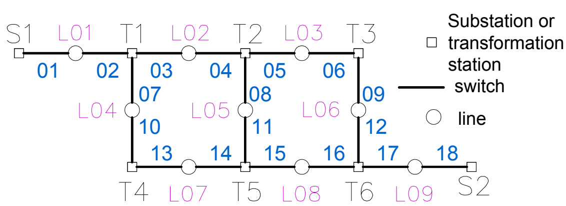

Figure 2: Representation of the model network.

switch name	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18
element before switch	S1	L01	T1	L02	T2	L03	T1	T2	T3	L04	L05	L06	T4	L07	T5	L06	T6	L09
switch set	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1
element after switch	L01	T1	L02	T2	L03	T3	L04	L05	L06	T4	T5	T6	L07	T5	L06	T6	L09	S2

Figure 3: Representation of Figure 2.

During the whole optimization process two representations of coded solution - one for genetic algorithm usage and another for the criteria function evaluation process is used. The representation used for GA is describes a non-oriented graph where vertices stand for the elements of network i.e. substations, transformation stations, overhead lines, cables etc, and switches represented by the graph edges. Example of the network topology is shown on Figure 1, its representation for GA purposes is on Figure 2, encoded equivalent of Figure 2 is shown on Figure 3 on the row "switch set". The GA representation is used to split the network to radial subnetworks by the modified Depth-first search (DFS) algorithm described in (Paar, 2008). Logical division of the network to subnetworks is essential for the evaluation process and also it is one of the conditions of the practical network operation.

4.2 Evaluation of the Solution

The evaluation is composed of the 1) cost of power losses calculation and 2) a penalization calculation for given continuity standard (Finnish continuity standard at system level or Portuguese continuity standard at single-customer level is used). Before evaluation an individuum is transcoded into the second representation using the Breadth-first-search algorithm (BFS). Contrary to DFS, BFS transforms the subnetwork to a structure without switches where vertices are represent substations or transformation stations and edges represent overhead line and cables. This structure allows to the steady state calculation and also determines the placement of so called protection zones in all the radial subnetworks. Protection zone are the areas affected by interruption of power supply on particular cable leading to the consequent continuity standard violation and penalization.

4.2.1 Power Losses Costs Calculation

The first evaluated criterion is focused on power losses cost. Power losses are calculated by using steady state calculation with power consumptions specified by electric currents and are independent from the voltage applied to their terminal point. These simplifications cause calculation to suffer from lower accuracy comparing to the power-flow calculation methods, such as the Newton-Raphson or Gauss-Seidel method. The main benefit is faster calculation and with satisfactory resolution of results (convergence of aforementioned iteration methods cannot be guaranteed). Costs of power losses (in €/year) are given by:

$$n_p = c_l \, P_l \, T_l \qquad (1)$$

where c_l is a specific unit on a middle voltage level, P_l is power losses of whole network and T_l is utilization time of power losses.

4.2.2 Valuation of Penalization Standards

The second criterion is made of the total number and the total duration of power supply interruptions evaluated by specified continuity standard. Number and duration of the outage is provided by the reliability model using Monte Carlo method. The reliability model is based on direct generation of random failures given by probability distribution based on statistic numbers of annual supply interruptions. The set of interruptions numbers is generated with one year time step for selected individual network components together with corresponding interruptions duration. This technique is described more in detail in (Dětřich, 2006). One of the main advantages of this approach is that it provides the results even for limited range of input data of examined network.

Every generated outage is bounded to specific networks elements. Each element fall within a specified protection zone whose size and topology is given with by the network topology and is defined as a protected part of the network by single protection element located directly in feeders or in important switch stations. The outage in any single element affects the whole protection zone where element is located and all protection zones fed by the affected protection zone. Number of affected zones and network elements gives the number of disconnected customers and the total duration of interruptions, the amount of non-delivered power to customers (in kWh) and enables calculation of the financial penalization for a given standard.

4.2.3 Finnish Continuity Standard at System Level

The Finnish continuity standard is used by Finnish Energy Market Authority and belongs to so called system level continuity standards which regulate the power quality without opportunity of direct payment to customers. The penalization payment is a part of complex metrics to set the network charges and also to evaluate the efficiency of whole network. The standard is described in (FEMA, 2007) (Paar, 2010).

4.2.4 Portuguese Continuity Standard at Single-customer Level

Portuguese standard expresses the maximal number of interruptions per year and maximum interruption duration annually. The limits specified in the standard are distinguished according to the voltage levels (HV, MV and LV) and population density. As Finland's standard was focused on system level, the computation is aimed to the Portuguese single-customer standard and excluded Portuguese standard at system level (Paar, 2010), (CEER, 2005).

4.3 Genetic Algorithm

The optimization of power network configuration leads to combinatorial problem with huge solution space where classical computation methods fail or don't bring useful results. Using the global optimization method can enable solution of such problems. The selected optimization method is quite basic implementation of the Genetic algorithm. The application uses GA with tournament selection, single point crossover, random mutation and elitism. Following chapters describe the main modifications done to solve the described problem.

4.3.1 Initialization

The initial population of GA is created by a specific function. The usage of binary coding of solution by switch setup is does not by itself guarantee proper network topology (like as feeding all parts of the network or radial structure of subnetworks). For small network, the quantity of non-allowed solution may not be problematic but it grows with the network size. Therefore the modified Depth-first search algorithm (MDFS) that includes some random features is used to guarantee viability of the initial population.

4.3.2 Fitness Function

The fitness function is designed as a weighted sum of two input parameters and a penalization function given by following formula:

$$\text{fitness} = \alpha\, n_p + \beta\, n_C + \gamma \tag{2}$$

where α and β are balance coefficients, n_p is power losses costs of whole network and n_C is penalization costs given by selected continuity standard. Function γ is used to discriminate inappropriate solutions (out of set limits) and is determined by this formula:

$$\gamma = \left(d_1 \cdot \sum_{i=1}^{n} \operatorname{cond}\left(\left| \Delta u_i \right| \geq \Delta u_{\max} \right) + \right. \\ \left. + d_2 \cdot \sum_{i=1}^{n} \operatorname{cond}\left(I_i \geq I_{\max} \right) \right) \cdot \Gamma \tag{3}$$

where d_1 and d_2 are weighting coefficients, Δu is a voltage drop vector in the network, Δu_{max} is maximal permitted voltage drop, I_i represents vector of currents flowing in the network and I_{max} is maximal current-carrying capacity, Γ is specific penalization.

4.3.3 Crossover

The classical single point crossover operator does not make sure that the new individual will represent a valid solution so it had to be modified. After the crossover, the comparison is made between offspring with one of parents. The result of comparison is parent solution with -1 numbers at all genes where offspring chromosome differs. The offspring is then corrected through a correction algorithm to repair all the damaged genes. This way ensures viability of the new generation while saving the computational time too since is not necessary to investigate all parts of the network but only the "damaged" one.

5 SIMULATION AND RESULTS

The results of the optimization show how the selected continuity standards affect the output parameters SAIFI (System Average Interruption Frequency Index that express average number of interruptions that affected customer per year; A similar parameter - SAIDI is focused on the average interruption duration) and power losses on the model of real middle voltage (22 kV) cable network.

The network covers area between two substations (110/22 kV) which together feed over 44

800 customers by 288 power transformation stations. The power network contains more than 300 cables and 628 section switches or circuit breakers.

The GA setup was following:

- 600 generations
- 16 individuals in one population (1 elite)
- crossover probability 0,95
- mutation probability 0,1

5.1 Results

The stochastic nature of genetic algorithm requires more optimization runs to be done. To show valuable results, each of the result graphs (Figure 4-6) contains, selected simulation run with duration close to the arithmetic average of all tested solutions (fitness function) and the maximum and minimum (both dotted line) of the fitness function for all the individuals for solution on current situation (original solution without any optimization, dot-and-dashed).

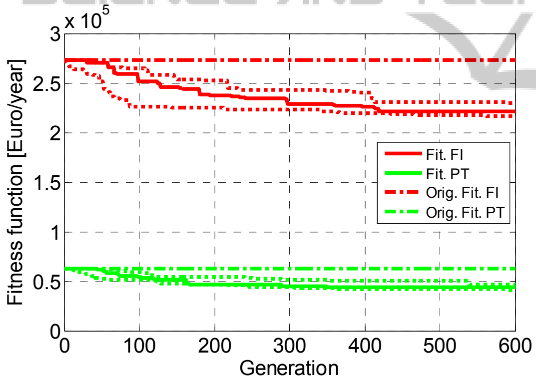

Figure 4: Duration of fitness function for Finnish and Portuguese continuity standards.

The overall penalization between the Portuguese and Finnish continuity standards is not directly comparable because of the differences in both approaches (system versus customer oriented). Each continuity standard serves for the different purposes; the Finnish standard is part of the complex metrology hence given total values of penalization do not affect the distribution companies directly. In simulations the Portuguese standard does not reach as high values as the Finnish but it must be noted that the direct impact to distribution company money is present since the penalization may make important portion of the network operational costs (Figure 4 shows the differences between fitness functions that shows the approximate difference in the operation costs of the network between the original and the optimized topology. The optimized version shows the decreased amount of money spent for penalizations approximately by a factor of 5.

To illustrate the difference in the reliability, SAIFI and power losses are showed on Figure 6. As it can be seen, the SAIFI parameter for the case of Finnish standard was decreased by 10%.

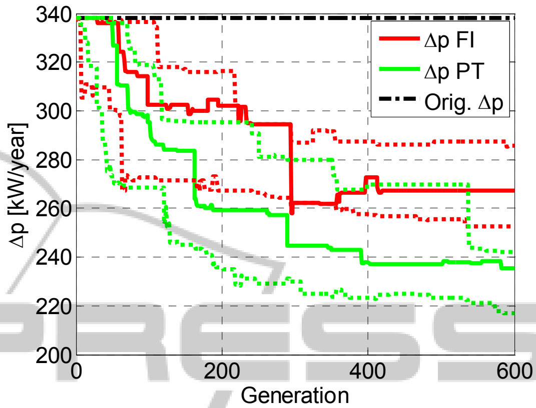

Figure 5: Evolution of power losses during generations for Finnish and Portuguese continuity standards.

Even more interesting is the impact to the power losses (see Table 1). The total power losses were decreased by 20% for optimization to the Finnish standard or even by 30% for the Portuguese on. Figure 5 depicts higher decrease of the power losses for simulations with the Portuguese standards. As can be seen on Figure 6, parameter SAIDI during optimization is improved but second part of optimization returns back close to original value. The Finnish standard is less affected by power losses costs in criterion function though the decreasing of power losses in this optimization is shown as well, the improvement of SAIFI and SAIDI parameters indispensible compare to Portuguese continuity standard.

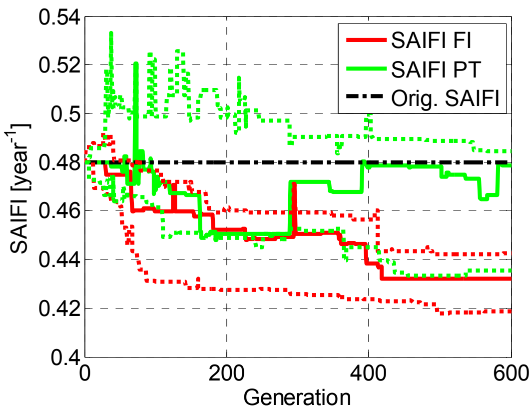

Figure 6: SAIFI duration during generations.

Table 1: Results for Finnish and Portuguese continuous standards.

standard	penalisation	SAIFI			SAIDI			ΔP		
	final	orig.	final	δ	orig.	final	δ	orig.	final	δ
	10^3 Euro	$year^{-1}$	$year^{-1}$	%	min/year	min/year	%	kW	kW	%
FI	220	0,48	0,43	9,9	32,6	29,3	10,4	338	267	21
PT	43,5	0,48	0,48	0,2	32,6	32,5	0,4	338	235	30

6 CONCLUSIONS

The article describes application of the genetic algorithms to the problem of the distribution network reconfiguration with the multi-criterion function with the aim to minimize the interruption of energy supply penalisation and at the same time also to minimize the power losses costs. Details of the algorithm caused by the combinatorial nature of the problem were described. The application was tested on model of a real MV cable network for two continuity standards.

The results show that power losses are inconsiderable part of multi-criterion function mainly when Portuguese continuity standard is used. The results imply that significant savings could be reached for very negligible expenses in the distribution networks.

The future work will be focused to the optimization with truly multi-objective nature.

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