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Distribution network operation optimization using artificially intelligence techniques

PhD thesis – abstract
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The distribution networks (DN) have in general a meshed structure but in normal condition are working unmeshed (as required to coordinate the protective devices, the voltage control etc.), as spanning tree radial networks. Obviously, considering the physical possibilities of sectioning the network, there are a lot of solutions to obtain unmeshed structure. Optimal reconfiguration of DN has the purpose to find the right solution which minimizes the real power losses on the entire network, following at the same a set of technical and economical constrains. Normally, the real power loss will be higher compared with the operating in meshed network, looking for the unmeshed solution which will "damage" less the situation from this point of view. The optimization problem can be approached also in a multi- objective way, the objective function (OBF) adding terms like: the voltage level improving, network elements loading balancing, reliability increasing, minimizing the number of switching operations needed, optimizing the distributed generation (DG) source, the cost of unpowered consumers, improving some environment matters etc.

The DN reconfiguration is a large size optimization problem with a powerful non-linear nature. Beside the classical techniques of solution based on the mathematical modeling and graph theory, stand out lately a large number of papers which use a series of simple heuristic techniques (Sequential Switch Opening – SSO, Branch Exchange – BE etc.) and meta-heuristic (Genetic Algorithm – GA, Particle Swarm Optimization – PSO, Artificial Neural Networks – RNA, Harmony Search – HS, Tabu Search – TS, Simulated Annealing – SA, Ant Colony Optimization – ACO, Artificial Bee Colony – ABC, hybrid methods etc.).

In this context, the topic of PhD thesis fits in the current concerns of the distribution networks management related to ensure optimal conditions of operation from all points of view. The thesis has as main goal the elaboration of effective methods, based strongly scientifically, optimal reconfiguration of the DN, utilizing simple heuristic techniques and meta-heuristic (based on using GA). The elaborated methods are finished with original solving techniques, implemented in software tools which use effective the possibilities given by the programming application and calculation system available in this moment.

The application started from small test systems developed by Electrical Power Engineering Department, Politehnica University of Timişoara (Test 13) and long-established IEEE test systems (IEEE 30, IEEE 33, IEEE 123 etc.), after that passing to the real large size distribution networks such as Enel Distribuţie Banat and Electrica Muntenia Nord. On grounds of "size", for the PhD presentation have been selected three DN: one test system type (IEEE 33) and two real, large size, belonging to Enel Distribuţie Banat (Timişoara DN and Timiş DN). The obtained results and the submitted conclusions are relevant both for distribution operators and especially for Enel Distribuţie Banat. The PhD thesis, written on 206 pages, is structured on 8 chapters, introduction, 5 electronic attachments and a bibliographic list, containing 61 figures, schemes, histograms and 71 tables. The bibliography includes 238 titles, noticing the presence of representative papers both those classic one as well as those relatively recent, published in the country or in prestigious magazines abroad.

Chapter 1 covers the introductory part. It includes the framing and the justification of the PhD topic in the context of the present state of the Electric Power Systems (EPS) development, of DN, among worldwide and our country's preoccupations. It follows the brief presentation of the contents for each chapter of the thesis. The conclusion shows both the way in which research was carried out in preparation of the PhD thesis (doctoral) thesis (publications, contracts, software tools) and the prospects for further research.

Chapter 2 is a summary of the present context and the EPS evolution in general, worldwide, on European and national level, focusing on the DN situation. The first part includes a presentation of the actual electric power field development, with a series of details concerning the electricity consumption at each level. The second part refers exclusively to Romania, as the focus is on transmission and distribution system operators, on the structure of the Power

Transmission Networks (PTN) and distribution, highlighting both their degree of wear and their modernization concerns (including the reduction of their Real Power Losses – RPL). The electric power field evolution in general and of EPS especially introduces a series of complex peculiarities with a high influence over other activity sectors which leads to a sustainable development in line with the environment issues. In the end, there are a series of conclusions and stand out the own contributions related to this chapter.

In the discussed context and taking into account the fact that concrete applications refer to DN in Romania, figure 1 represents the DN structure and figure 2, shows the 8 distribution areas [ANRE].

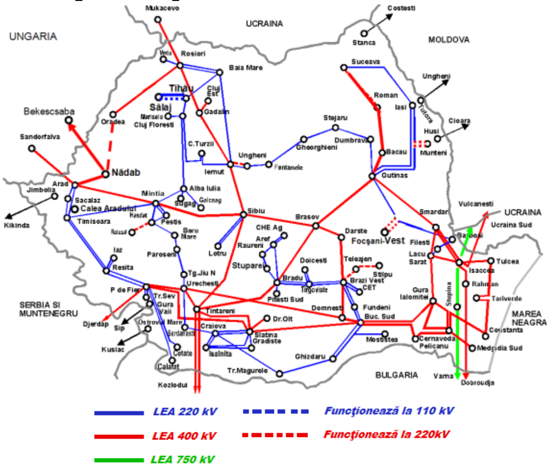

Fig.1. Power Transmission Network (PTN) structure

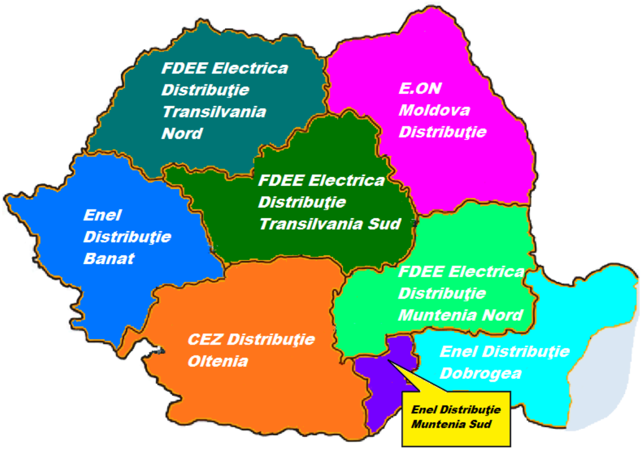

Fig.2. The map of the 8 distribution areas

From a thesis's point of view, knowledge of the power losses level (real power losses – RPL) at various voltage levels of DN (110 kV, medium voltage and low voltage (Table 1)) is of interest [ANRE].

Table1. The evolution of real power losses (RPL) in electricity distribution networks

Distribution System Operator	Voltage level	Real Power Losses [%]						
		2011	2012	2013	2014	2015	2016	2017
Enel Banat	î.t.	0,69	0,69	0,64	0,68	0,81	0,73	0,88
	m.t.	3,82	3,71	3,65	3,61	3,69	3,67	3,95
	j.t.	17,17	14,78	15,21	14,71	14,36	14,56	14,44
Enel Muntenia	î.t.	0,70	0,72	0,71	0,63	0,58	0,68	0,68
	m.t.	4,39	4,35	3,68	3,78	3,85	3,59	3,54
	j.t.	21,20	21,13	16,42	17,64	18,52	16,96	16,79
Enel Dobrogea	î.t.	1,01	1,16	1,35	1,94	2,16	1,63	1,86
	m.t.	3,90	4,02	4,15	3,95	5,17	6,13	5,55
	j.t.	18,18	16,00	15,52	14,06	14,06	12,71	13,90
CEZ Oltenia	î.t.	1,46	1,20	1,45	1,68	1,23	1,11	1,18
	m.t.	4,89	5,02	5,21	5,34	4,10	3,74	4,00
	j.t.	27,36	26,32	23,74	24,64	23,44	20,75	19,14
E.ON Moldova	î.t.	0,87	1,06	0,96	1,02	1,01	0,86	1,02
	m.t.	2,66	2,85	2,85	2,97	2,68	2,68	2,74
	j.t.	20,49	22,37	21,77	20,45	19,65	17,39	16,26
Electrica Muntenia Nord	î.t.	1,02	0,98	1,01	1,06	1,02	0,87	0,82
	m.t.	7,36	7,01	7,17	6,87	6,61	6,59	6,37
	j.t.	15,73	14,85	15,29	16,16	17,02	15,17	15,51
Electrica Transilvania Sud	î.t.	1,15	1,24	1,14	1,10	1,04	0,97	1,03
	m.t.	4,13	4,06	4,22	4,21	4,23	4,06	3,67
	j.t.	19,38	18,13	17,57	18,42	17,51	16,96	16,62
Electrica Transilvania Nord	î.t.	1,60	1,17	1,36	1,19	0,98	1,13	1,21
	m.t.	4,62	4,59	4,58	4,49	4,69	4,56	4,64
	j.t.	14,17	12,93	12,08	12,29	12,22	11,69	10,98

The chapter highlights the need for a unitary vision and of sustained efforts for optimizing the DN function both to provide a quality service under improved reliability as well as the reduction of RPL (including the DN reconfiguration).

Chapter 3 presents the current methods of solving the Distribution Networks (DN) reconfiguration within the complex Electric Power Systems (EPS). It is mentioned that it is a large size optimization problem, nonlinear (or linear), usually real and integer variables.

The methods of resolving the discussed problem (DN reconfiguration) may be divided into two main categories:

- optimization methods based on classical mathematical modeling techniques – linear programming, mixed linear programming, non-linear programming, dynamic programming etc. [Haghighat2016], [Lopez2016], [Toure2015];
- heuristic techniques (Sequential Switch Opening – SSO, Branch Exchange – BE) [Ding 2015a] and meta–heuristics (Genetic Algorithm – GA, Evolutionary Algorithms – EA [Abdelaziz2017], [Vieira2016], Particle Swarm Optimization – PSO [Tuladhar2016], Artificial neural networks – ANN [Fathabadi2016], Harmony Search – HS [Muthukumar 2017], Tabu Search – TS [Kuihua2016], Simulated Annealing – SA [Nie2012], Ant Colony Optimization – ACO [Ameli2017], Artificial Bee Colony – ABC [Sulaima2014], Artificial Immune System – AIS [Souza2016], Charged System Search – CSS, Biogeography Based Optimization – BBO etc.).

The use of hybrid methods is also possible, after combining two or more methods and including some techniques of a fuzzy type. Subsequently it reviews the methods actually used to solve the applications, the others will be presented in detail in the thesis.

The SSO heuristic methods (Sequential Switch Opening) start the reconfiguration process from the DN initial full meshed network which means that all switching devices are closed. They consist essentially of an ordered opening sequence of such equipment, until a final radial structure is obtained. Usually, the power losses increase in relation to those fully meshed aiming at each step at the finding of that maneuver which leads to the least improvement. Obviously, the situations in which unpowered loads (unpowered islands in the network) would remain. The search is completed when a radial pattern has resulted. As with any heuristic method, there is no guarantee that the solution found is the optimal one (but it certainly is just quasi-optimal). [Zhu2015] Independence of the solution of the initial state of the switching equipment (the initial radial pattern of the network) is the major advantage. The various versions of the SSO method differ between them through the heuristic rules applied to the choice of network sectioning location, through a.c. power flow by definition method of single-objective or multi-objective optimization. The method is simple but it takes further measures to reduce computation time.

In [Gomes2005] formulating the reconfiguration issue is the classic one, with the aim of minimizing the real power losses while respecting the constraints on the amount of voltage in load bus and the power flow through elements in the network. At each step an exhaustive exploration of the disconnected possibilities is performed with a simplified calculation of the power flow. It is chosen that switching equipment which leads to the least power losses (after disconnection), under the conditions of a feasible way of operation. After obtaining the final radial configuration, an additional search is performed in the vicinity of open switching equipment (checking that the "neighboring" separators do not lead to regimes with less active power losses). After obtaining the final radial configuration, an additional search is performed around, each open switching equipment (checking that the "neighboring" separators do not lead to regimes with less power losses). It is estimated, that the computation time is quite large, due to the comprehensive (exhaustive) exploration, to the each iteration.

In [Raju2008] a similar method to the one above is used, noting that the additional search is made using a Branch Exchange-type heuristic algorithm (BE).

The method used in [Gomes2005] is further developed in [Gomes2006] via a series of enhancements designed to reduce the computation time. Determining the power flow is replaced by the power flow optimization (Optimal Power Flow – OPF) which incorporates submission with the constraints on the values of the voltages and the load of the network components. The exhaustive scan is performed by a sensitivity analysis within the OPF. As part of the final power flow consumption calculation, when losses on the entire network are determined, the discrete nature of the position of the switching equipment is reintroduced.

[Fajardo2008a] extends past concerns by taking distribution networks with multiple points of power, including when the costs of the delivered energy are different. [Fajardo2008b] provides a dynamic approach to the reconfiguration problem over a certain period of time, analyzing the situation for well-determined moments. At each step of the iterative reconfigure process, attempts are made to open the switching equipment related to the weakest loaded element network which is part of a closed mesh.

The additional item submitted in [Subrahmanyam2010] and in [Zidan2011] is to apply SSO-type methods to unbalanced networks. It consists of applying the SSO-type methods for unbalanced charging networks. In addition, [Zidan2011] takes into account the presence of distributed generation (DG) sources.

In [Prasanna2015] it is being used a SSO-type heuristic method similar to that in [Gomes 2005]. An improved "backward/forward" method [Rupa2014] is used for calculating the power flow. At each step of the reconfiguration process, the element network is determined for which the difference between the voltages at the two ends is minimal, and the corresponding switch equipment is opened.

Genetic Algorithms (GA) are part of the evolutionary algorithms (EA), they are mainly used to solve discrete optimization problems (combinatory), where population is represented by solutions in the feasible field of the problem, binary encoded and the main operators are those of crossover and selection (the mutation operators is one with little probability of application).

[Hong2005] use within the GA frame Prüfer binary encoding [Rothlauf2006] based on network buses instead of the usual one, based on sides (network branches). Yielding in chromosomes with a lower number of genes and the additional network radial branched test associated with the current reconfiguration solution is avoided. In defining OBF, it is noted that in its expression of terms that "penalize" the violation of the constraints [Kilyeni2015b] regarding to bus voltages (buses voltage), maximum permissible current through the network elements etc.

In [Mendoza2006] the attention is focused on improving adaptability and efficiency of the methods that use GA. The searching space is reduced by a new strategy for encoding and by new genetic operators ("accentuated crossover" and "directed mutation"). The smaller population is obtained through the network elements which form a "system mesh", which means that all individuals represent a feasible solutions (unmeshed network), only the verification of technical constraints is necessary. [Mendoza2009] transforms the standard reconfiguration problem into a multi-phase sequence, adding to the objective function expression four components linked to operational reliability. It is being used a GA of micro-genetic algorithm (μAG) capable of generating optimal Pareto-type solutions.

The preoccupation to increase GA efficiency is also reflected in [Carreno2008]. The efforts are pointing towards two directions: providing efficient coding, to facilitate the implementation of genetic operators, and avoiding loss of population diversity. The encoding is based on the branch of the system (network elements), first n–1 genes of chromosomes (n – number of buses) corresponding to the respective radial structure and the following r–(n–1) connecting branches, which would close meshes (r – number of network elements). In this way an initial population can be generated which includes radial topologies only and the crossover (recombination) and mutation operators can be implemented to generate new radial structure started from the original (current) topologies. After the crossover (recombination) phase there is a local improvement in order to maintain the population diversity.

The new elements raised by [Mendes2013] refer to entering the reconfiguration strategy of the transformer tap-changer adjustments with voltage regulation under load. The DN large applications for each solution shall be performed a.c. power flow. Along a classical GA a memo algorithm is also used – a classic GA extension with a local search technique to avoid premature locking of the algorithm.

[Storti2014] presents a problem of reconfiguration approach to "smart grid" networks that include in addition to distributed generation (DG) sources and also FATS-like equipment. Multi-objective approach aims to minimize real power losses and maximize the load of distributed generator sources, the constraints relationships being those regarding the values of voltages and network elements loading. In order to reduce GA related time computation, a simplified representation of the network based on graph theory is used.

[Eldurssi2014] approaching the reconfiguration as a multi-objective optimization problem. Weighting the components of objective function (OBF) – (normalized values – adjusting "common denominator") can be made in a deterministic way or in fuzzy manner. To overcome the difficulties linked to weights setting, made use of a NSGA ("non-dominated sorting GA") version of GA – FNSGA ("fast non-dominated sorting GA"). NSGA shall use two criteria to define "domination" (or "non-dominated"): if a solution for all criteria it's not the worst than another solution and is strictly better to at least one criteria, then the first one is "dominant" compared to the second solution (the second is "non-dominant" compared to the first one). FNSGA – Operating with a single rank, which reducing the computational time. In order to determine whether a given topology is radial (unmeshed network) is used here a method based on the branch-bus incidence matrix. [Eldurssi2015] deepens the implementation of the FNSGA algorithm, by presenting a lot of consistent applications for larger scale distribution systems. A similar approach is presented even in [Vieira2016], where the OBF incorporates issues related to operational reliability of DN and of unavailability index of distributed generation sources.

In [Nafisi2015] presented the reconfiguration problem in a wider context, to finding the optimal unmeshed solutions over a day (for which is known hourly load curve). The OBF includes three terms: real power losses costs, switching operations costs and "penalty" constraint violations about bus voltages (voltage amplitude), network elements load (in manner from [Kilyeni2015b]).

The element of novelty brought by [Deng2016] is the application of a QGA (Quantum Genetic Algorithm), which use some of principles of quantum mechanics in the selection process and computation of objective function value, resulting a swiftly finding of favorable zones from the space of solutions.

In [Abdelaziz2017] the population size it's no longer a constant for each generation, but varying in the adaptively manner during the algorithm's evolution (Genetic Algorithm with VAriable Population Size – GAVAPS).

Shall be highlighted a special focus on the solution methods based on heuristic and meta-heuristic techniques, by preparing the ground for the following chapters, which refer to the concrete methods used in the thesis and achieved case studies. Is distinguished, critically, the fact that a small number of papers used an a.c. power flow, although the possibilities provided by the current computing technique allow this. Hence, the thesis used in all situations a robust calculation of the operational mode (regime). Also, many papers show applications only for small scale systems, make a sense of doubt over usage of the proposed methods for large scale DN. Within the thesis will be approached applications for the real DN more than 1000 buses.

Chapter 4 aims at artificial intelligence techniques used within the doctoral thesis and especially about GA. Besides the theoretical elements, a series of practical implementation aspects are also presented in order to solve the distribution networks reconfiguration. Both real encoded GA would be taken into account (used for power flow optimization, with consideration of the specific components of distribution networks) as well as GA with binary encoded (used in fact for solving the reconfiguration problem).

GA utilizes evolutionary computation. In general, an evolutionary computation technique is an iterative method to solve optimization problems based on a search procedure inspired by the biological evolution (of the Darwinist type). Potential solution population is used to solve the problem (compound elements of the population), which evolves through the iterative application of some stochastic operators. Natural evolution specific changes apply to seeking to guide the optimal population solution: selection (the "most valuable" elements of the population are favored – have increased chances to survive in the next generation and to participate in the coming of offspring generation), crossover (similar to nature multiplication – starting from two or more elements of the population, called parents, new elements called offspring are generated). Based on their quality, measured by the corresponding OBF value, offspring replace their parents. The mutation is used to ensure population's diversity – changes of a random nature on elements of the population are performed in such a way as to allow new features (genes) to appear, which only by crossing and selection would not have appeared within the population [Kilyeni2014b], [Rothlauf2006], [Sastry2014], [Solomonesc2013].

Depending on the way the population is constructed and how the evolution is carried out, evolutionary computation techniques fits in one category:

a) Genetic Algorithms (GA) which are used for solving some discrete optimization problems (combinatorial), where population is represented by solutions in the feasible field of the problem, binary encoded, and the main operators are those of crossover and selection (the mutation one have a little probability of application);
b) Evolutionary Algorithms (EA) are primary used to solve continuous optimization problems, where population is made up elements of OBF's definition field, encoded to real decimal values. The main operator is the mutation and crossover (recombination) is used. For the evolution strategies, self-adapting schemes of the control parameters have been developed.

The first step in configuring GA is represented by chromosomes encoding (no matter the fact that this is about binary or real coded GA). These can contain any number of variables and can be represented as string of variables or binary tree (spanning tree with binary values), integer, real, symbols or characters. The use of binary values is best suited to real chromosomes, but it would require a conversion algorithm, each variable being represented by several genes. Encoding with integer and real values allows direct access to the variables but reproduction operators are more difficult to implement.

The population incorporates all the possible solutions and has the role of maintaining them during the iteration. The size of the population shall be represented by the number of individuals and shall be determined by reference to the number of variables and the nature of the problem. The population's diversity is ensured by the number of different individuals who join it. To best cover your searching space needs to maintain diversity by choosing the appropriate population size and properly set up crossover operators. The initial population will be generated randomly following the type of encoding and the size of the population.

During the evaluation stage the chromosome decoding and each member of the population is evaluated. An OBF is defined for the evaluation of individuals within the population (a matching function– "fitness") measuring the quality of individuals. The higher the value of this function, the better the individual in question represents a solution.

The selection stage aims at choosing individuals that will have the chance to participate in reproduction. The selection is made based on the assessment from the previous step, through truncation selection, through competition, through the roulette wheel, etc. Selection methods should ensure on the one hand that the best individuals will be selected and on the other hand provide a smaller possibility and the most weaken individuals, with a view to preventing the solution from locking in optimal local conditions.

The role of reproduction is to introduce new genetic material to the population in order to scan the entire searching space. The reproduction operators (recombination and mutation) are applied with previously defined probabilities, so that not all parent pairs will create offspring and not all genes of the offspring will suffer mutations. The means of implementing reproduction operators is influenced by the way of chromosomes encoding.

Another concept used within GA is elitism. This requires copying the best solution from one generation to the next without any change. The iterative calculation process ends when the improvement of the solution is no longer significant during a number of established previously iteration (the optimal solution is achieved).

The personal contributions within this chapter are the creation of an original summary upon GA, as a distinct category from EA; mathematical model systematization for binary coded GA which will be used to solve the DN reconfiguration problem and for those with real coded one, needed to solve the optimization problem of the power flow.

Chapter 5 aims to developing and solving the mathematical model of the optimal reconfiguration of the DN. The first part contains the mathematical model of optimal reconfiguration of DN. The second part deals with problems to be solved in any reconfiguration method – a.c. power flow, concerned optimization the operational regime. All reconfiguration methods used within the thesis used an a.c. power flow, to find a solution of the mathematical modeling using numerical methods "classical techniques" specific of nonlinear systems equations. To optimize the operational range shall be used a meta-heuristic method based on applying a GA, completed with specific items of DN. The third part of the section presented a "classical" heuristic method by solving the optimal reconfiguration problem, of SSO-type – Sequential Switch Opening of the network (until obtaining an unmeshed structure). The fourth part is intended to address the problem being discussed in chapter 4, using artificial intelligence techniques, in this case the genetic algorithm. Based on previous experience applying evolutionary computing techniques both targets the actual reconfiguration method (using a binary coded GA) as well as to optimization the operational regime (GA encoded with real values). The a.c. power flow is performed in a classic manner, with a decoupled Newton algorithm [Kilyeni2015b].

The mathematical model concern to DN which includes n buses (N – buses multitude) and r network elements (R – network elements multitude), from which n_l are power lines (L – subset of power lines), n_t are transformers (T – subset of transformers) and n_s are switching equipment (S – subset of switching equipment).

From the point of view of the discussed problem, disregards the inactive buses (considered load buses with a zero consumption of regarding to real and reactive power), there are two distinct types of nodes: generator buses or voltage control buses (where there are active power sources), in number of g (G – subset of generator buses), respectively; load buses (where there are not active power sources), in number of c (C – subset of load buses).

When operating in meshed structure, one of the generator buses is considered slack bus (e, $e \in$ G). When operating in unmeshed (radial) structure, each subsystem includes only one generator bus (a single feeding point), that being even slack bus.

The mathematical model which describes optimal reconfiguration of the DN presented a nonlinear optimization problem with constraints, with a large size, of the mixed type (integer and real variables):

$$F(x_1, x_2, \cdots x_n) = \text{MINIM} \tag{1}$$

$$g_j(x_1, x_2, \cdots x_n) = 0, \quad \text{j} = 1, 2, ..., p \tag{2}$$

$$g_j(x_1, x_2, \cdots x_n) \le 0, \quad \text{j} = p+1, p+2, ..., m \tag{3}$$

Where the variables x_1, x_2, ..., x_n are integer and real (binary), reflecting the position of the switching devices (connected or disconnected); objective function F – real power losses across the entire network; the equality constraints (EC) deal with power balances across the network buses (specific a.c. power flow), and the inequality constraints (IC) relate to lower and upper limitation of some sizes.

Being that it's about DN reconfiguration, to the mentioned constraints is adding two additional considerations:

- At each step of settling (resolving) the network must be connected (each load must be powered, that there are no unpowered, "islands");
- The solution of the reconfiguration must lead to unmeshed topology (radial branched), in other words, must to include a number of subsystems equal to that of feeding points.

In these circumstances, the discussed mathematical model can be defined in the following way (noting that searching for that combination of disconnected elements that lead to minimum value of OBF, under conditions to respect for all constraints):

- variables:

⇒ state variable (those corresponding to power flow):

$$\delta_i\,,\, i \in N \setminus e\,,\; P_{ge}\,,\;\; U_i\,,\, i \in C\,,\;\; Q_{gi}\,,\, i \in G \qquad (4)$$

and, eventually,

$$P_{ij}, Q_{ij}\,,\, ij \in R\,,\; S_{ij}\,,\, ij \in R \text{ sau } I_{ij}\,,\, ij \in R \qquad (5)$$

⇒ control variable:

$$z_{ij}\,,\, ij \in S \qquad (6)$$

where, $z_{ij}\,,\, ij \in S$ are binary variables that indicate status of network element, value "0" meaning "connected" (closed) and the value "1" – "disconnected" (opened);

- constraints:

⇒ equality type constraints (power balances in buses):

$$\begin{cases} P_i(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K}) - P_{gi} - P_{ci} = 0\,, & i \in N \\ Q_i(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K}) - Q_{gi} - Q_{ci} = 0\,, & i \in N \end{cases} \qquad (7)$$

where, the active and reactive power P_i and Q_i have the following expressions:

$$\begin{cases} P_i = U_i^2 \cdot G_{ii} + \sum\limits_{\substack{j \in N \\ j \neq i}} U_i \cdot U_j \cdot \left[G_{ij} \cdot \cos(\delta_i - \delta_j) + B_{ij} \cdot \sin(\delta_i - \delta_j) \right], & i \in N \\ Q_i = -U_i^2 \cdot B_{ii} + \sum\limits_{\substack{j \in N \\ j \neq i}} U_i \cdot U_j \cdot \left[G_{ij} \cdot \sin(\delta_i - \delta_j) - B_{ij} \cdot \cos(\delta_i - \delta_j) \right], & i \in N \end{cases} \qquad (8)$$

$\underline{Y}_{ij} = G_{ij} + j \cdot B_{ij}\,,\; i = \overline{1,n}\,,\; j = \overline{1,n}$, being the elements of bus incidence matrix $\underline{Y}_n$;

⇒ inequality type constraints (lower and upper limitation of some sizes):

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}\,, \quad i \in G \qquad (9)$$

$$U_i^{\min} \le U_i \le U_i^{\max}\,, \quad i \in N \qquad (10)$$

$$S_{ij}^{\min} \le S_{ij}(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K},\boldsymbol{\Omega}) \le S_{ij}^{\max}\,, \quad ij \in R \qquad (11)$$

where, apparent power, $\underline{S}_{ij} = P_{ij} + jQ_{ij}$ have the following expressions:

$$\begin{cases} P_{ij} = \;\; U_i^2 \cdot (G_{\ell\, ij} + G_{\ell\, i0}) - U_i \cdot U_j \cdot \left[G_{\ell\, ij} \cdot \cos(\delta_i - \delta_j) + B_{\ell\, ij} \cdot \sin(\delta_i - \delta_j) \right] \\ Q_{ij} = -U_i^2 \cdot (B_{\ell\, ij} + B_{\ell\, i0}) - U_i \cdot U_j \cdot \left[G_{\ell\, ij} \cdot \sin(\delta_i - \delta_j) - B_{\ell\, ij} \cdot \cos(\delta_i - \delta_j) \right] \end{cases} \qquad (12)$$

$$S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \qquad (13)$$

⇒ the network must be connected (each load must be powered, that there are no unpowered, "islands");

⇒ the network must be unmeshed topology (radial branched);

- objective function (OBF) – real power losses across the entire network:

$$FOB = \sum_{ij \in R} (\Delta P_{ij}) = Minim \tag{14}$$

where, (ΔP_{ij}) represent real power losses on the network element *ij*.

Arguing in terms of de graph theory [Kilyeni2015b], DN corresponds to undirected graph (we're interested in network typology): graph vertices correspond to the network buses, and the edges of the graph correspond to network elements (*n* vertices and *r* edges). Unmeshed the DN mean finding a spanning tree of concerned graph (further referred to as the original graph).

In the essence of its definition, a spanning tree of the graph, include *n*-1 edges. Unmeshed the DN involves removing the *r*-(*n*-1) edges from the original graph, while maintaining connected status and for the elimination of meshes. In other words, need to be "disconnected" *r*-(*n*-1) network elements (must be ensured "sectioning" of the DN in *r*-*n*+1 points). The original graph containing *r*-(*n*-1) cycles, or, in associated terminology of the DN, comprises *r*-(*n*-1) meshes. The spanning tree, match basically, a radial branched network.

The elements presented above are valid under the conditions in which DN have only one feeding source (feeding point) (*g*=1). If the DN's (Distribution Networks) are complex definitely exists a lot of feeding points. The network shall be sectioning in such a way that each load is powered only from a single source. Under these circumstances, the un-meshing process will result in obtaining to some radial branched network for every source (feeding point). Will should to be remains connected *n*-*g* network elements, which means elimination of *r*-(*n*-*g*) meshes. In other words, must be "disconnected" *r*-(*n*-*g*) network elements (must be ensured "sectioning" of the DN in *r*-*n*+*g* points).

In chapter 7, will be presented the case studies (main applied research), in which will be made further details on how the values *r*, *n* and *g* shall be established in concrete way (besides the actual medium voltage distribution network itself, on the regarded schemes appears a piece of high voltage network).

To implement the SSO-type (Sequential Switch Opening) reconfiguration method, shall be starting at from a meshed structure of the DN (all the switching devices are closed). Is determined the number of the necessary steps to achieve unmeshed optimal structure and is performed, step by step, un-mesh process of DN, in the conditions of respecting constraints and minimize the OBF value. The algorithm of this method is as follows:

a) based on the information concerning DN, shall be established the list of un-mesh possibilities;

b) based on the information concerning size and structure of the DN, shall be calculated the number of steps *np* in order to achieve unmeshed network (the number of sectioning points or the number of switching devices that must be opened):

$$np = r - (n - g) = r - n + g \tag{15}$$

c) shall be calculated the power flow for a complete meshed network;

d) shall be optimized the operating regime as determined in the previous point;

e) to a random step *k*, *k* = 1, 2, ..., *np* in the process of achieve unmeshed network is determined the lowest loading power line from the current list of possibilities (of achieve unmeshed network) set out in point a) – potential candidate for the current step of achieve unmeshed network;

f) "disconnect" the line in question (Power Line);

g) shall be verified if the network resulting from operation from point f) remained "connected";

h) if the network remained connected going to point i), otherwise shall be updated the current list of possibilities (of achieve unmeshed network) by "elimination" current solution of achieve unmeshed network and return to point e) to finding a feasible solution (the counter *k* remains unchanged);

i) shall be calculated the power flow for the current network structure, resulting from step f);

j) shall be optimized the operating regime as determined in the previous point;

k) shall be augmented the value of the step counter k and shall be verified the condition for termination of achieve unmeshed network: if $k > np$ the calculation is complete and switch to point l), otherwise switch to point e) for the next step of achieve unmeshed network;

l) the current step of solution (unmeshed network) is representing the optimal solution of reconfiguration.

To *implement the GA type (Genetic Algorithm) reconfiguration method* shall be starting at from a complete meshed structure of the DN. Shall be established the list of un-mesh possibilities (sectioning) of the DN; shall be randomly generated a initial set of reconfiguration solutions, the set of solutions iterative improving by evaluation procedures, selection, recombination etc., when the current optimal solution can no longer be improved. The best version of the last set of solutions shall be considered as the optimal solution of reconfiguration.

Each chromosomes of population indicate the state of the switching equipment (connected/disconnected). Because the states of the switching equipment's can be represented in ("0" and "1") characters from binary alphabet, is justified to using the basic version of genetic algorithms (binary encoding).

The chromosome will have length of *ns* (the number of switching equipment's):

$$\mathbf{x_i} = \{x_{i1}, x_{i2}, \ldots, x_{ins}\}, \quad i = 1, 2, \cdots, n_c \tag{16}$$

In the evaluation phase, for every chromosome, will be attributed a value based on OBF. The calculation is considered complete if for an iterations number, previously established, the solution can no longer be improved. Under these conditions the algorithm steps are the following:

a) based on the information concerning the DN, list of unmeshed possibilities is hereby established;

b) based on the information concerning size and structure of the DN, shall be calculated the number of sectioning points np or the number of switching devices in order to achieve unmeshed network:

$$np = r - (n - g) = r - n + g \tag{17}$$

c) is initializing randomly, with "0" and "1" values, the genes of n_c chromosomes that belong to the population – np genes with the "1" value and ns–np genes with the "0" value:

$$\mathbf{x}_i^0 = \{x_{i,1}^0, x_{i,2}^0, \ldots, x_{i,ns}^0\}, \quad i = 1, 2, \cdots, n_p \tag{18}$$

d) for every chromosome checks out if the related DN has a unmeshed structure or not. If the network is not unmeshed, shall be generated successively other chromosomes, until to obtain unmeshed structure;

e) shall be calculated the power flow for the related configuration of every chromosome and shall be optimized the operating regime (mode) (for satisfy certainly the constraints about voltage magnitude in buses and loaded element network);

f) the initial population shall be evaluated based on OBF value, the best individual (elitist procedure) being saved in $\boldsymbol{x}^0_{elit}$:

$$f(\boldsymbol{x}_{elit}^0) = \min\{FOB(\boldsymbol{x}_i^0)\}, \qquad i = 1, 2, \ldots, n_c \tag{19}$$

g) to a random step k in the process of computation, k = 0,1,2,..., one of the selection procedures described in chapter 4 is to be applied; after the process of selection will be result a population $\boldsymbol{x}_{sel,i}$, $i = 1, 2, \ldots, n_{sel}$, whose members will have stand a chance to recombination $n_{sel} = n_c / 2$:

- is forming $n_{pr} = \chi \cdot n_c / 2$ pair of chromosomes which will be subordinated to crossover and $n_{pc} = \; = n_c / 2 - n_{pr}$ sets that will be copied unspoiled (uncorrupted);
- are formed two offspring (at each iteration) from ones n_{pr} sets, through crossover (Single Point Crossover or Multi-Point Crossover), according to the procedures indicated in chapter 4, in accordance with the condition referred to in point c) of the algorithm;

- shall be calculated the number of chromosomes, from population formed in the previous step, which will be changed by mutation: $n_{cm} = \mu \cdot d \cdot n_c$, the genes are changed in the manner described in chapter 4;
- the first chromosome from the resulting population of the previous step is replaced with the best one from the old population:

$$\boldsymbol{x}_1^{k+1} = \boldsymbol{x}_{elit}^k \qquad (20)$$

- for every chromosome of the current population verify if the related network has an un-meshed structure or not. If not, then shall be generated successively other chromosomes (by already described procedures or randomly generated), until to obtain unmeshed structure;
- shall be calculated the power flow for the related configuration of every chromosome and shall be optimized the operating regime;
- shall be evaluated based on OBF value, the best individual (elitist procedure) being saved in $\boldsymbol{x}^k{}_{elit}$:

$$f(\boldsymbol{x}_{elit}^k) = \min\{FOB(\boldsymbol{x}_i^k)\}, \qquad i = 1, 2, ..., n_c \qquad (21)$$

h) shall be verified the condition for completion the computations – when the improvement of the $FOB(\boldsymbol{x}_{elit})$ (objective function) value is no longer significant for a certain number of iteration: if this condition is satisfied the iterative calculation process is considered complete and switch to point j), otherwise, shall be augmented with value 1 the step counter *k* and switch to point e);

j) the structure defined by final form of $\boldsymbol{x}_{elit}$ establishes the optimal solution of reconfiguration of the DN.

Besides adjustment of analysis and optimization methods regarding to operating regimes of the large scale Electric Power Systems (EPS), regarding DN, the following original contributions are highlighted:

- completion of the mathematical model used to solve optimal reconfiguration problem of Electric Distribution Network (EDN);
- clarification of the number of "meshes" (according to graph theory) respectively, elucidation the number of necessary sectionalizing of the DN in order to ensure a unmeshed structure for reconfiguration solutions, depending on the number of feeding points;
- developing an heuristic SSO-type method for optimal reconfiguration of DN, that starts from a meshed structure and based on Sequential Switch Opening process, until to obtain a connected network with unmeshed topology (radial branched);
- development of a binary encoded GA (Genetic Algorithm) method to solve optimal reconfiguration problem of DN.

Chapter 6 aims to present the software tools utilized in studies of DNR: the one that solve the power flow optimization in large scale distribution networks, respectively the one that solve actually the optimal reconfiguration problem. The computational programs (computation schedules) are based on the software tools presented in [Solomonesc2013], related to transmission network expansion planning within Electric power systems, which have been modified in accordance with the specificity of DN and the reconfiguration studies (instead of the expansion planning). The software tools use working environment provided by Matlab package. Interfaces allow the balance between at database level and with package of PowerWorld software tool [PowerWorld], Power (developed at Electrical Power Systems Department) [Kilyeni2015b] and MatPower [MatPower]. All the software tools allow the configuration of genetic algorithm parameters and choosing specific options of the problem, when relevant.

Chapter 7 is entirely original, which is the main applied research part of this work. The DNR is solved by implementing the heuristics and meta-heuristics techniques. The application started from small test systems developed by Electrical Power Sysyems Department, Politehnica

University of Timişoara (Test 13) and well known IEEE test systems (IEEE 30, IEEE 33, IEEE 123 etc.), after that passing to the real large distribution networks such as Enel Distribution Banat and Electrica Muntenia Nord. On grounds of "size", for the PhD presentation have been selected three DN: one test system type (IEEE 33) and two real, large size, belonging to Enel Distribution Banat (Timişoara DN and Timiş DN).

The first part of this chapter shows the results obtained for IEEE test systems (used in order to verify and calibrate the reconfiguration algorithm drawn up within the thesis framework and of the developed software tools), the second part of this chapter deal with Timişoara DN (102 buses) and third part concerns Timiş DN (1037 buses).

Timişoara DN covers a significant part of the network (from the area of Timişoara city) served by Enel Distribution Banat. Timiş DN shapes in detail the entire network (from the area of Timiş country) within Enel Distribution Banat. For each network, are shown both of the network elements topology and parameters as well as the power flow results of the basic regimes. Also, is given a set of details about unmeshed regimes obtained from the reconfiguration process, by specifying the potential quasi-optimal solutions (together with practical recommendations concerning real DN). The reconfiguration studies have been determined with both of the following methods presented in chapter 5: the heuristic SSO-type (for reasons of "space", in PhD thesis appear only the IEEE 33 test system), respectively that one which using a GA (in PhD thesis occur all three distribution networks).

Regarding the concrete manner of presentation and discussion of the result's obtained, stands out the following aspects with general validity for all the analyzed networks:

- are presented both the topology and the parameters of the network elements, as well as the power flow results for the basic regimes;
- the reconfiguration studies are undertaken for the basic regimes of IEEE 33 test system, respectively for real and normal (usual) regimes in case of Timişoara DN and Timiş DN;
- the analyzes may be extended, without difficulty, also to possibly other operational regimes;
- the optimal solution of reconfiguration is described in detail, with all the separation points of resulted from the considered network, along with the typical dates of the related regime;
- in addition to optimal solution, are shown other possible variants (quasi-optimal solutions), resulting from optimization process, or based on the optimal solution analysis;
- the reconfiguration studies shall be completed with practical recommendations, which are useful for distribution system operators (especially for the real networks – Timişoara DN and Timiş DN);
- shall be analyzed also the detailed issues related to GA evolution manner, of optimal reconfiguration.

For reasons of space, shall be presented just the results of the IEEE 33 – DN test system (Fig. 3, meshed topology, one single source (1 generator bus), 34 buses, and 38 network elements).

For the considered regime the real power consumption are 3,44 MW, the reactive one are 1,65 MVAr, the real power output are 3,561 MW, the reactive one are 1,688 MVAr. The voltage level is in admissible range (including all the buses). Total real power losses are 0,121 MW – 3,52 % (of which 0,029 MW at 110 kV level, which means practically the transformer, and 0,092 MW – 2,67 % – at 10 kV level, which means practically the power lines at 10 kV level).

Prior to conducting the reconfiguration, shall be determined the number of sectioning points np (the number of "meshes" of the network or by "cycles" according to graph theory), in other words the number of steps which should be done until completely unmeshed network. The number of network elements r = 38, the number of buses are n = 34 and the generator buses g = 1, which means np = 5 (as described in chapter 5).

In the first place the reconfiguration was made with the quasi-optimal heuristic method of SSO-type. It was considered that there are all unmeshed possibilities (every line section may be disconnect at both ends). The solution of reconfiguration is presented in figure 4, which means to disconnect the following sections 8-9, 10-11, 15-16, 18-19 and 26-30).

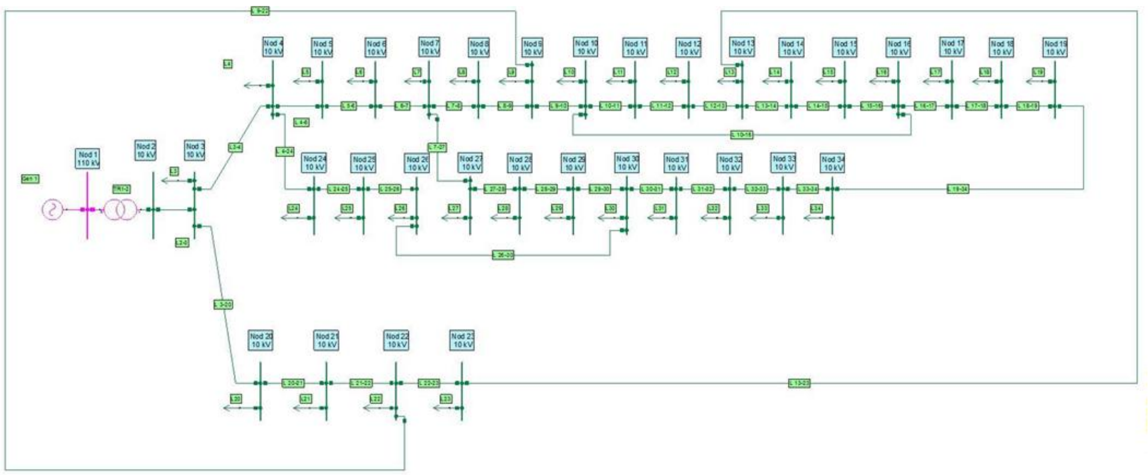

Fig. 3. IEEE 33 test DN structure

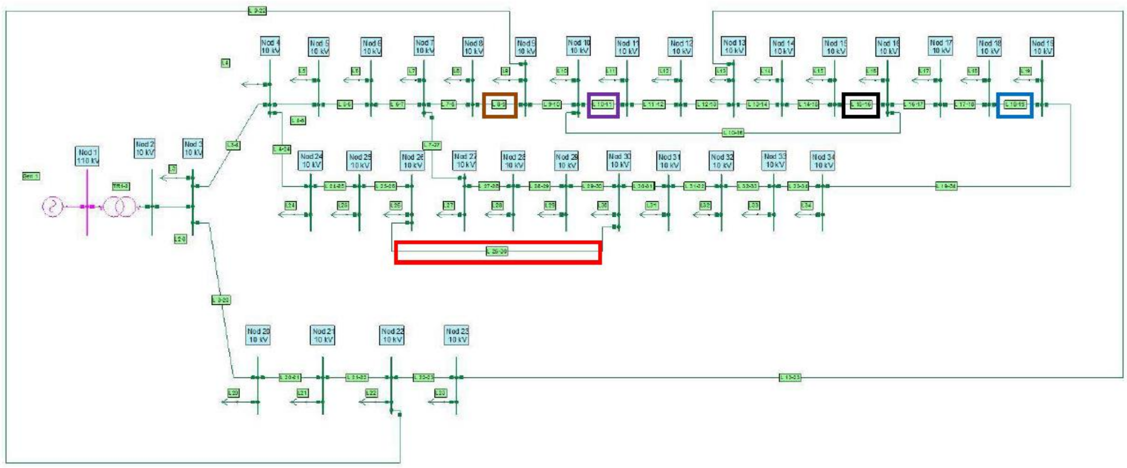

Fig. 4. IEEE 33 test DN optimal structure of reconfiguration

For the obtained regime after reconfiguration the real and reactive power consumption remain unchanged (3,44 MW, respectively 1,65 MVAr), the real power output are 3,568 MW, the reactive one are 1,699 MVAr. The voltage level is in admissible range (including all buses).

Total real power losses are 0,128 MW (of which 0,030 MW at 110 kV level, respectively 0,0978 MW at 10 kV level). Compared with initial regime where the DN had a completely meshed structure, the real power losses increased from 0,121 MW to 0,128 MW, which means an increase of 5,6 % (absolutely justified by passing from the completely meshed structure (regime) to the unmeshed structure).

The reconfiguration using GA method, lead to a similar solution with the previous one, explainable fact through small size of the network.

Figures 5 and 6 present the evolution of the algorithm to establish the optimal solution of reconfiguration. Figure 5 deals with this issue in terms of the relative value of OBF, corresponding to the current optimal solution, achieved by reporting to the first iteration.

Analyzing the figure 5 shall be highlighted the fact that the value of OBF shows the improvements during the entire progress of the algorithm, with the following amendments:

- in figure are represented the values of the OBF only for the iterations where have occurred thereof significant changes (what can see by analyzing the blue curve from fig. 5);
- the total improvement of achieved for optimal solution is 23,4%;
- at iteration 28 has been achieved a gain of 16,2% (compared to iteration 1), which means an average value of around 3% for a set of 5 iterations;
- at iteration 52 has been achieved a gain of 5,9% (compared to iteration 28), which means an average value of around 1,2% for a set of 5 iterations;

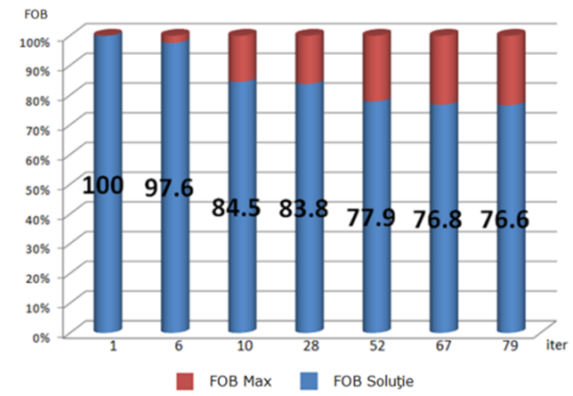

Fig. 5. The evolution of the OBF value (compared with the value to the first iteration)

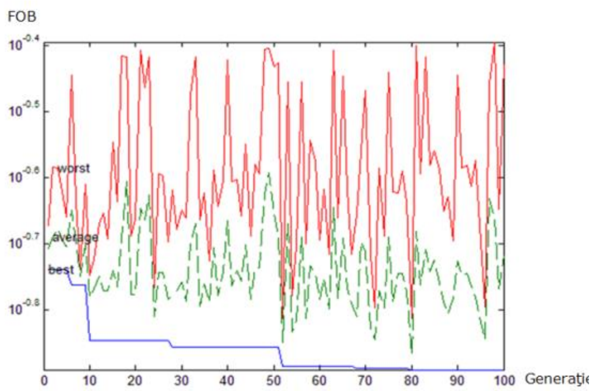

Fig. 6. The evolution of the OBF value (the best value, the average value and the worst one)

- at iteration 67 has been achieved a gain of 1,1% (compared to iteration 52), which means an average value of around 0,4% for a set of 5 iterations;
- at iteration 79 (final solution) has been achieved a gain of 0,2% (compared to iteration 67), which means an average value of around 0,08% for a set of 5 iterations;
- being that the average value, throughout the entire optimization process, the gain for a set of 5 iterations is around 1,5%, the downward trend of this value, shown in the previous points, is normal: 3 %, 1,2 %, 0,4 %, 0,08 % (is observed a much more intense improvement in the first part of the optimization process and a lower gain later).

Analyzing the figure 6 highlight similar conclusion with what has been set out above, (evolution of the value "best" – blue color). Also, is observed the evolution of the average value for the entire population, being more "irregular", corresponding to the current iteration ("average" – green color), respectively the value of the worst one ("worst" – red color).

Additional analyses allow drawing conclusions concerning the quasi-optimal solutions, in other words the network areas (zones) where it needs to be established conditions for decoupling (fig. 7):

- mesh 1: 26-30, 30-29, 29-28;
- mesh 2: 33-34, 34-19, 18-19, 18-17;
- mesh 3: 10-11, 11-12, 12-13;
- mesh 4: 13-14, 14-15, 15-16;
- mesh 5: 8-9, 9-22.

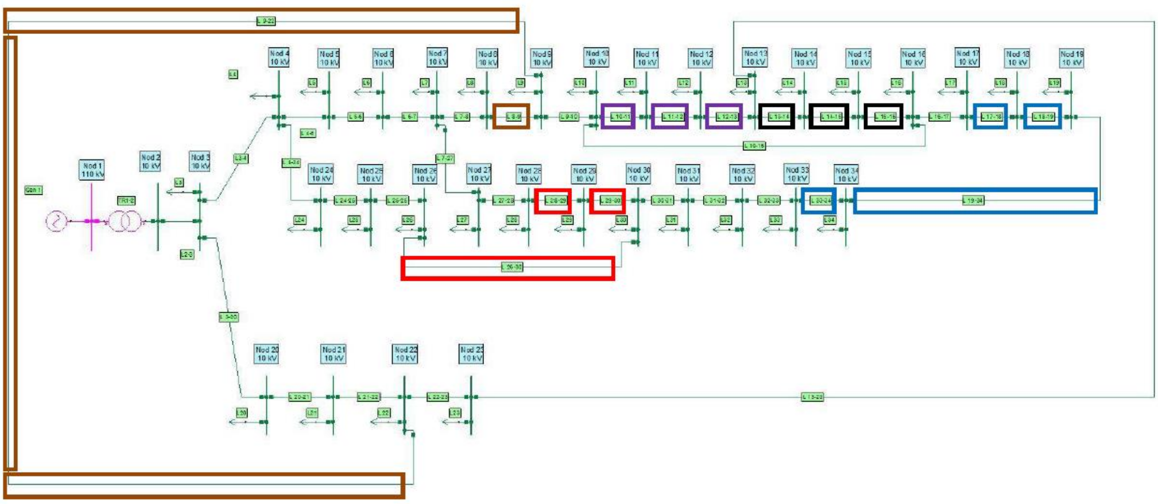

Fig. 7. The domain of the practical solutions of reconfiguration for IEEE 33 test DN

Finally, it can be stated that conclusions resulting during the entire chapter, related to optimal reconfiguration of DN, are of a special utility both for Distribution System Operators (DSO), in general, and also for Enel Distribuţie Banat, in particular.

Chapter 8 includes the general conclusions and systematized presentation of the original contributions of the author (mentioned mostly to the description of the previous chapters), as well as highlighting the directions and the perspectives provided by the present work for continuing the research and application of the results and the obtained experience. The methodologies and the developed computational software tools, are of general application, by providing an efficient tool for the Electric Distribution System Operators, as well as to other specialized entities, in the field of DN.

The results presented in thesis have been and will be harnessed within some scientific research contracts signed between Politehnica University of Timişoara, Research center for analysis and optimization of Electric Power Systems (EPS), and Enel Distribution Banat, Enel Distribution Dobrogea, Electrica Muntenia Nord and other economic operators. In addition, the reasons for establishing the theme of (doctoral) PhD thesis, was also the interest shown by the Distribution System Operators as regards the operational regimes (schemes) and the reconfiguration of DN.

As well, part of the results obtained in the PhD thesis framework have been published and are in the process of publishing. It is noted that of the total of 7 own papers until now, 3 are published in the country and 4 in abroad. 6 papers are ISI-indexed, one being indexed in other Indexed Databases (ID). Also were presented and a series of papers within the project POSDRU "Increasing the attractiveness and the performance of the PhD and post-doctoral training programs for researchers in engineering sciences – ATRACTING". ID 159/1.5/S/137070.

Both the theoretical and the practical analysis made in the PhD thesis framework, as well as the results presented, opened a set of perspectives and directions to following further enhancement of research in the field of optimal reconfiguration of EDN:

- refine of settling (resolving) methods based on using genetic algorithms, in order to increase the efficiency and improve their performance;
- implementation of other types of methods based on artificial intelligence techniques;
- multi-objective approach of the optimization problem, by completing the objective function with a couple of terms, properly (suitable) weighted, aimed at the voltage level improving, network elements load balancing, operational reliability improving, minimizing the number of switching operations needed, inclusion the cost of unpowered consumers, improving some environment matters (minimal emissions) etc.;
- resolving (settling) the reconfiguration problem by considering the sources of distributed generation;
- probabilistic approach of some element parts of the discussed problem;
- extension of the analysis to other Distribution Networks (DN), managed by diverse Distribution System Operators from Romania.

The electronic attachments (CD) offers a set of elements and also a detailed results about the main applied research part (cap. 7) concerning databases used for the complex case studies as well as to considered operating regimes and to obtained results (primarily the Timiş DN distribution system, with over 1000 buses).

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