MODELLING OF MV DISTRIBUTION GRID IN SOFTWARE PRAO

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INTRODUCTION

For control over power grid, several softwares are developed that perform load flow and voltage calculation, monitor operation scheme, enable manipulation with switching devices, acquisite measurements and events in the network. On the other hand, for network planning, softwares demand complex calculations. Beside monitoring existing state of the grid, it's necessary to optimize supply bounderies, calculate losses and costs to find optimal variant of grid development on a certain area.
In “Elektrodistribucija-Beograd” (EDB) software PRAO (developed in “Electricité de France” - EDF) for network planning is in use since 2002 and several analyses were completed for huge consumer areas. In order to use this software for different analyses a great number of data were entered in the base. This paper will show which values are necessary for functioning of PRAO and how were solved many problems that occurred during data entering and further use of software.

BASIC DATA FOR PRAO

Type file

Characteristics of all network elements were entered in PRAO data base:
1. lines:
    - type of line (overhead/cable)
    - material of a conductor (Al, Cu, Al/Fe)
    - type of insulation (paper, XHE)
    - cross-section of a conductor (mm^2)
    - termic current (A)
    - longitudinal reactanse (Ω/km)
    - longitudinal resistance (Ω/km)
    - capacity (nF)

- overload coefficient in backup conditions (k=1 for non-insulated lines and k=1.2 for cables and twisted lines)

2. transformers
   - grafic symbol
   - primary voltage (kV)
   - secondary voltage (kV)
   - rated power (MVA)
   - overload coefficient in backup conditions (k=1.25)
   - Joule losses (kW)
   - iron losses (kW)
   - short-circuit voltage (%)

3. nodes – in this category are included busbars, substations 10/0,4 kV/kV, incoming-outgoing cubicles and bays, transformer cubicles and bays, line disconnectors and also "common" nodes which can be poles where section of a line begins or inserted nodes in a single-line diagram of a substation with two busbars. For each node was entered:
   - grafic symbol
   - node category – source, feeder, single

For all elements is entered:
- name of a particular element
- price in kEUR (x10^3 EUR) – for lines per km
- lifetime of an element (years)

In Type file was entered percentage of annual load growth (load evolution) for substations 110/X kV/kV and 35/10 kV/kV. These values were calculated based on load forecast for the planning period of 20 years.

PRAO parameters

Basic data are also parameters relevant for electric and economic calculations, reliability and quality. Parameters needed for electric calculations are:
- maximal allowed voltage drop in normal and backup conditions – allowed value in MV grid is ±10% in both cases
- annual load growth rate (load evolution) – default value 1,5% wasn't used because load forecast was peformed for all substations 110/X kV/kV and 35/10 kV/kV
- adjustment levels of tap-changers

Parameters needed for power lines' reliability are based on data available within EDB:
- average longitudinal annual fault rates for 10 kV overhead lines (31,02/(year,100km)), cables (25,6/(god.,100km)) and twisted lines (27,5/(god.,100km))
- average longitudinal annual fault rates for 35 kV overhead lines (8,7/(year,100km)) and cables (4,8/(god.,100km)) are specially entered while drawing these particular lines
- annual fault rate of short (from 1 s up to 3 minutes) and very short outages (shorter than 1 s) per 100 km – records of very short outages shorter than 3 minutes don't exist in EDB

Parameters concerning quality of electric energy supply for all types of 10 kV lines are obtained from relevant services within EDB. For manual and remote resupply time, parameters are taken from lit. [2]:
- remote control resupply time – 6 minutes are determined
- manual resupply time – 120 minutes are determined
- average duration of outage for all types of 10 kV lines (average duration of repair) – 660 minutes for overhead lines, 2460 minutes for cable lines and 1560 minutes for twisted lines

For calculation of Joule and iron losses costs, energy not supplied (ENS) and discount of costs, following parameters are entered:
- duration of maximal load (h)
- costs of Joule losses and iron losses (kEUR/kW), according to lit. [3] – cost of Joule losses depends on duration of maximal load. Therefore, costs were calculated for different durations

and entered in the file Prao.ini. For determined duration T_{max}=3500h, cost of Joule losses is 0,08778 kEUR/kW.

- discount rate – value in our country is 9%
- lifetime of a network element – considered value for all types of elements is 40 years
- first and second limit of energy not supplied (MWh) and their prices (kEUR/kWh)
- minimal duration of a long outage
- value of cut-off power

Two prices are used for calculation of energy not supplied costs and they depend on value of ENS. According to lit. [4], price 1,5 EUR/kWh for ENS is taken for our country and the price doesn't depend on the amount of ENS. Therefore, values of the first and second limit of ENS are too high, which means that the amount of ENS will always be lower than the first limit and the price will always be constant. EDB still hasn't got obligation to pay costs for ENS to consumers and taken price for analyses was 0,5 EUR/kWh for ENS. At the time of performing these analyses, this price for ENS was 10 times greater than the price for distributed electric energy. Given values from the above are shown in Figure 1.

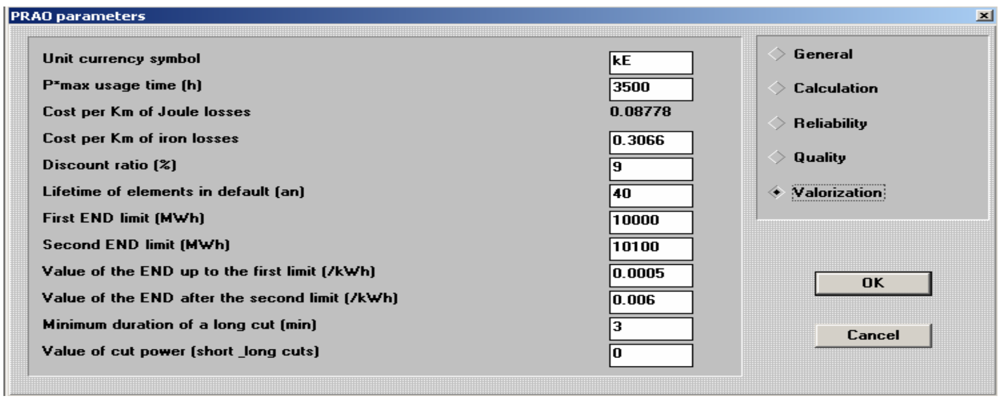

Figure 1: Values of parameters for costs calculation of Joule and iron losses and ENS, value of discount rate

Data for calculations of reliability and supply quality of consumers are entered for defined consumer area. These data are for substations on that area, separately for MV and LV consumers. Average and maximal durations of outages (cut time) are entered, number of long, short and very short outages of substations and also maximal duration of outage for power lines. Values are taken from EDF data base because there are no adequate fault statistics in EDB.

Drawing the grid

For precize drawing of the grid, different backgrounds can be used (with command: Add background file), entered with their real geographic coordinates:

- pictures *.bmp and *.gif – scanned pictures, aerial photos
- ACAD drawings *.dxf – PRAO creates a picture from this form with *.exe file

Geographic backgrounds for analized consumer areas were scanned geographic maps with cable lines, entered by relevant coordinates for the Republic of Serbia. All necessary data were gained from services in EDB.

During creation of the grid, specific element is chosen from the completed data base of grid elements. That element gets it's name and automatically gets parameters given to that type of element (node, line, transformer). Location of the element is specified directly on the screen. Positioning of power lines is also on the screen, between two nodes. If a power line consists of several segments, each segment is defined with type of line, cross-section and length. Each line or segment on a single-line diagram of a substation can contain switching device, if one exists, and can be defined whether it's manual or remote controlled. Names and locations of source substations 35/10 kV/kV, 110/35 kV/kV, 110/10 kV/kV and 110/35/10 kV/kV are entered specially. Single-line diagrams are drawn for substations 110/X kV/kV and TS 35/10 kV/kV. All elements of the grid can be added, modified and deleted.

Part of the grid on consumer area Zeleznik is shown in Figure 2 and single-line diagram of substation 35/10 kV/kV “Ripanj” is shown in Figure 3.

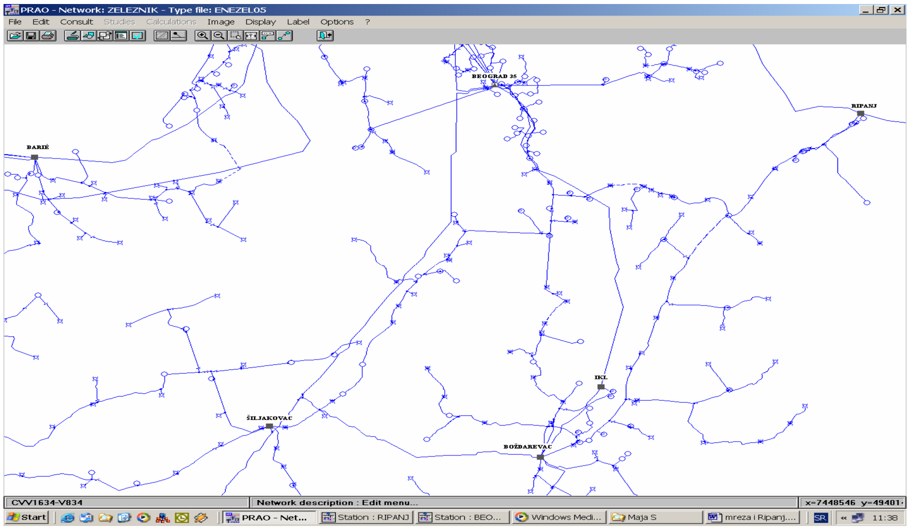

Figure 2: 35 kV and 10 kV grid consumer area Zeleznik – small circles are S/S 10/0,4 kV/kV, S/S 35/10 kV/kV are Baric, Siljakovac, Bozdarevac, IKL, Ripanj and S/S 110/35/10 kV/kV/kV is Beograd 35 (Sremcica)

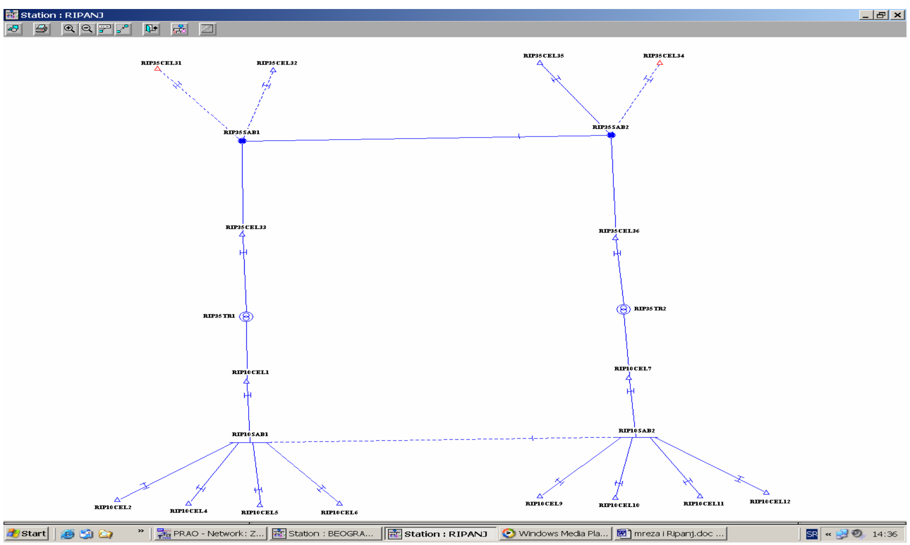

Figure 3: Single-line diagram of the S/S 35/10 kV/kV “Ripanj” with 4 lines 35 kV, disconnector in busbars 35 kV, 2 transformers, disconnector in busbars 10 kV (open) with 2 sections and 4 feeders 10 kV per each busbar section

CALCULATIONS IN PRAO SOFTWARE

Installed power is entered for all substations. Maximal loads of grid elements are entered based on data taken from Annual report of grid elements' loads during winter season on consumer area of EDB. Calculations can begin after completion of the grid. First of all, planning period for analysis of the grid has to be defined and it's maximal duration can be 30 years. From the initial year until the last year, software calculates total load in the grid, overload of elements, iron losses, Joule losses and maximal voltage drop in the grid. If some of the determined technical criteria is exceeded, software gives information about that element in the grid: visually – the element gets adequate color, which can be seen in the Legend and textually – in global and detailed results given in EXCEL file.

“Daily quality” calculations give simulation of the fault and supplying possibilities in backup conditions. It serves for estimation of reliability and supply quality of consumers on a certain area. Simulation of supply restoration can be followed on the screen, step by step: operation of protection devices and loss of supply of location with fault, examination of supply restoration with automatic devices, remote controlled switching devices, manual switching devices and shows the best variant of supply restoration. This way it can be seen if complete restoration of supply is possible after certain fault or only particularly, taking into account defined technical criteria in backup conditions and also cut-off power and number of consumers without supply until fault reparation. Following simulations are available:

- single incident (fault on a single segment) – simulation of fault on a chosen feeder. The result is number of short and long outages for LV and MV consumers due to permanent faults and duration of long outages for LV and MV consumers. Total cut-off power is calculated, energy not supplied and it's cost, fault cost and annual expected cost of fault.
- treatement on each feeder (fault on one or several feeders) – program gives the same costs as for the fault on a single segment, for every chosen feeder with fault. Besides, for MV and LV consumers it gives number of very short, short and long outages and average annual fault duration, number of LV and MV consumers on the feeder with fault.
- incident in a source substation – results are the same like in the first two cases but they refer to a greater number of consumers and results are given for every feeder.
- multiple incident – in this case, one or several segments can be chosen, not only feeders. The results are the same like in the previous cases.

Second type of calculations concerns reliability of a source substation, simulates possibilities of power reserving by remote controlled switching devices if outage of that substation occurs (outage of source node) or outage of many feeders supplied from that substation:

- totally – outage of all feeders from a substation
- parcially – outage of certain number of feeders

Maximal number of openings/closings of switching devices can be chosen, which can be seen at the end of the simulation within results. Results also give number of openings/closings, list of segments which were open/closed, list of nodes with restored supply, percentage of total power in the grid with restored supply and percentage of LV and MV consumers with restored supply.

Third type of calculation is optimization of operating scheme. Optimization can be performed in every year within planning period. Basic criterion is elimination of overload in the grid and additional criterion can be minimization of Joule losses and/or voltage drop. Beside that, calculation can be performed and automatically stopped in the year when overload appears, with possible choice of additional criterion – excessive voltage drop. If optimization of overload is chosen during this calculation until critical year, additional criterion can be minimization of Joule losses and/or voltage drop. Optimization of operating scheme can also be performed between two defined years. It means that an year is defined within planning period until when calculations are performed and the program stops in the year when some of the determined criteria is reached. Criterion for this calculation is also minimization of Joule losses and/or voltage drop but without optimization of overload.

One of the solutions for defined criteria is change of supply boundaries in the grid, which is the result of optimization and the software gives a list of switching devices that have to be open/closed to reach that operating state.

If the problem cannot be eliminated with change of supply boundaries, some intervention has to be done on the grid. The software itself doesn't give solutions, PRAO user does it by creating certain work. Group of all works on the grid within planning period is called “strategy” in PRAO terminology and each strategy has it’s name. Benefit/cost ratio (BCR) can be calculated for every work. Work is profitable if BCR ≥ a (discount rate). This way, group of the most profitable works can be formed and determine the year for implementation of every work. At the end of the strategy, Strategy Balance Sheet is calculated. It represents total cost of the whole strategy – costs of all investments, faults, Joule losses, iron losses, maintenance. All mentioned costs are given per year and their sum as well, discounted on the initial year of the strategy. Tehnically and economically best variant for development of the grid on the analyzed area can be determined based on calculated costs of each strategy.

PROBLEMS DURING CREATION OF DATA BASE AND GRID IN SOFTWARE PRAO

At the beginning of drawing the grid, huge problem was lack of geographic backgrounds and data for all parts of EDB's consumer area. Documentation existed for cable grid and that's mostly urban area, where 35 kV and 10 kV lines are mostly cables. With these geographic backgrounds, positions of substations 10/0,4 kV/kV and lines could be determined. However, small number of geographic backgrounds existed for rural area, where lines are mostly overhead. Those backgrounds weren't scanned and coordinates for entering with software PRAO couldn't be precisely determined. Also, lengths and types of all 10 kV lines weren't specified on them. Since 2002 until nowadays, all existing cable and geographic backgrounds were computer scanned, aerial photos of EDB's consumer area were obtained from Insistute for Urbanism and coordinates for each photo were determined. During 2005, group of backgrounds for rural area was formed, with positions of substations 110/X kV/kV, 35/10 kV/kV and 10/0,4 kV/kV and lines 10 kV. Connection of all available backgrounds for urban and rural area into one entire background started this year. Each one of those backgrounds that has it's name and number will be entered into PRAO with it's real coordinates. On the other hand, diagram of 10 kV connections between substations X/10 kV/kV and 35/10 kV/kV with number of outgoing cubicles is available through local server. Data about type of line and length of every segment and installed power for substations 10/0,4 kV/kV were gathered.

The next problem was how to define electrical characteristics of network elements. Values from Internal Standard of EDB were taken for some types of lines and transformers. Some values were obtained from relevant services within EDB and others were determined based on technical reference books (Rade Koncar, MEP). Rated thermal currents, resistances and reactanses were estimated from technical reference books, taking into account that building and operation conditions of power lines defined in Internal Standard of EDB do not match standard conditions given in those reference books.

Prices of power objects and switchgear elements were estimated in cooperation with service for investments in EDB but unique price list doesn't exist within EDB. Therefore, prices for objects such as S/S TS 35/10 kV/kV, TS 110/X kV/kV, some elements of the switchgear (for example: equipment for a bay or cubicle, mounting of tone frequency control system etc.), prices for reconstructions and reparations of power lines, were estimated and entered separately in PRAO base as costs, in order to perform economic comparation of variants.

Beside selection of the most suitable mathematic method for load forecast, great problem during calculation of future loads were data about measured loads in the past. Reason for that is lack of remote control system in all substations TS X/10 kV/kV and errors in reading measured values. Next problem was change of supply boundaries on 10 kV grid. Because of that, size of consumer area of a certain source substation wasn't constant and there was a great variation of loads. Load forecast becomes difficult and errors occur. Elimination of these problems and realization of the most realistic load forecast is one of the main tasks for planners because it's entered in PRAO data base as annual growth rate (load evolution) for all substations X/10 kV/kV included in analysis.

Calculation wouldn't be possible without input of loads of 10 kV lines. Maximal load of 10 kV line supplied from substation X/10 kV/kV takes into account substations 10/0,4 kV/kV on one 10 kV line proportional to their installed powers, through “swell” coefficient. Another coefficient “swelling rate” exists in the software and that's in source substations 110/35 kV/kV and 110/10 kV/kV. Second “swell” coefficient was given between “source” node and the first line seen as feeder. In the performed analyses, “swelling rate” was given in order to make tranformer loads and load of the whole substation 35/10 kV/kV equal to measured loads according to Annual report of grid elements' loads.

Software PRAO isn't created for simultaneous analysis of several voltage levels. It gives correct results while analyzing 10 kV grid and different works on it. However, with described corrections it's possible to obtain directions for 10 kV and 35 kV grid development but it's necessary to analyze 10 kV grid separately, in detail.

Paralel work of lines and transformers exist in EDB grid but PRAO cannot analyze such operation. Instead of two lines, one line with twice bigger cross-section and adequate characteristics was drawn. That line is in operation (closed switching device) and the other identical line isn't (open switching device). Unfortunatelly, it helped to solve the problem but it doesn't give real operating scheme and there are errors specially in reliability calculation.

Another disadvantage is that models of two-windings transformers and auto-transformers as elements of the grid exist in PRAO but model of three-windings transformer doesn't. Therefore, model of three-windings transformer was created in Type file and it will be shown in this paper.

Model of a three-windings transformer

Based on known data about Joule losses between windings P_{Cun}^{ij}, iron losses $P_{Fe\,n}$ and short-circuit impedance between windings $u_{k\,ij}$[%], three impedances of a three-windings transformer can be calculated, according to equivalent scheme on Figure 4 and given formulas from lit. [5]:

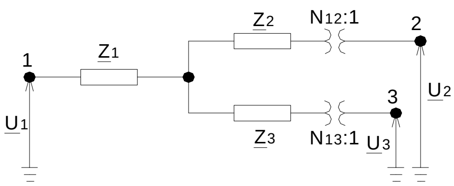

Figure 4: Equivalent scheme of a

three-windings transformer

$$P_{Cun}^{1} = \frac{1}{2}\cdot\left(P_{Cun}^{12} + P_{Cun}^{13} - P_{Cun}^{23}\right),\quad P_{Cun}^{2} = \frac{1}{2}\cdot\left(P_{Cun}^{12} + P_{Cun}^{23} - P_{Cun}^{13}\right)$$

$$P_{Cun}^{3} = \frac{1}{2}\cdot\left(P_{Cun}^{13} + P_{Cun}^{23} - P_{Cun}^{12}\right)$$

Resistances on the primary side of a transformer are calculated based on Joule losses between windings:

$$R_{12}=\frac{P_{Cun}^{12}}{S_n^2}\cdot U_{n1}^2,\quad R_{13}=\frac{P_{Cun}^{13}}{S_n^2}\cdot U_{n1}^2,\quad R_{23}=\frac{P_{Cun}^{23}}{S_n^2}\cdot U_{n1}^2$$

Impedances are calculated according to formulas: $Z_{ij}=\frac{u_{k\,ij}(\%)}{100}\cdot\frac{U_{n1}^2}{S_n}$, ij = 12,13,23

Reactances are calculated from impedances and resistances from above: $X_{ij}=\sqrt{Z_{ij}^2-R_{ij}^2}$

Resistances and reactances of equivalent impedances of a three-windings transformer can be calculated according to formulas:

$$R_1=\frac{1}{2}\cdot\left(R_{12}+R_{13}-R_{23}\right),\quad R_2=\frac{1}{2}\cdot\left(R_{12}+R_{23}-R_{13}\right),\quad R_3=\frac{1}{2}\cdot\left(R_{13}+R_{23}-R_{12}\right)$$

$$X_1=\frac{1}{2}\cdot\left(X_{12}+X_{13}-X_{23}\right),\quad X_2=\frac{1}{2}\cdot\left(X_{12}+X_{23}-X_{13}\right),\quad X_3=\frac{1}{2}\cdot\left(X_{13}+X_{23}-X_{12}\right)$$

$\underline{Z}_i=(R_i+jX_i)$, i = 1,2,3

For example is taken three-windings transformer 110/35/10 kV/kV/kV of rated power 31,5 MVA with following characteristics:

S_n=31,5/21/21 MVA	P_{Fe}= 24,62 kW	
$P_{Cu\,12}$ = 79,7 kW	$P_{Cu\,13}$ = 91,7 kW	$P_{Cu\,23}$ = 74,1 kW
$u_{k\,12}$ = 9,4%	$u_{k\,13}$ = 14,16%	$u_{k\,23}$ = 3,81% (for 21 MVA)

S/S 110/35/10 kV/kV/kV "Beograd 35 (Sremcica)" has two three-windings transformers of rated power 31,5 MVA with characteristics given above. Single-line diagram of this substation is shown in Figure 5.

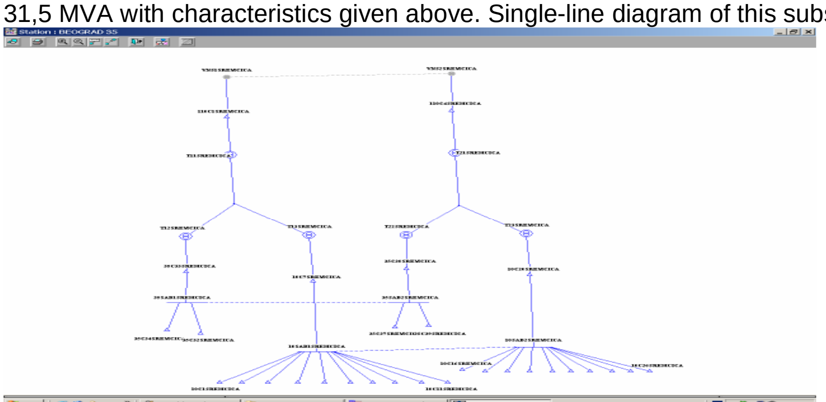

Figure 5: Single-line diagram of substation 110/35/10 kV/kV/kV "Beograd 35 (Sremcica)"

For each three-windings transformer, three two-windings transformers are created with voltage ratio:
T11 110/110 kV/kV
T12 110/36,75 kV/kV
T13 110/10,5 kV/kV

Impedances on 10,5 kV voltage level are calculated:

$\underline{Z}_1^{10,5kV}$ = (0,00541+j0,5185)Ω

$\underline{Z}_2^{10,5kV}$ = (0,00776-j0,0255)Ω

$\underline{Z}_3^{10,5kV}$ = (0,01076+j0,2245)Ω

Impedance $\underline{Z}_3^{10,5kV}$ is given to transformer T13 110/10,5 kV/kV. Impedance $\underline{Z}_1^{10,5kV}$ is calculated on 110 kV voltage level and given to transformer T11 110/110 kV/kV and impedance $\underline{Z}_2^{10,5kV}$ is calculated on 36,75 kV voltage level and given to transformer T12 110/36,75 kV/kV:

$$\underline{Z}_2^{36,75kV} = m^2 \cdot \underline{Z}_2^{10,5kV} = \left(\frac{36,75}{10,5}\right)^2 \cdot \underline{Z}_2^{10,5kV} \qquad \underline{Z}_1^{110kV} = m^2 \cdot \underline{Z}_1^{10,5kV} = \left(\frac{110}{10,5}\right)^2 \cdot \underline{Z}_1^{10,5kV}$$

Iron losses were divided equally on all three two-windings transformers and with calculated impedances that gives following characteristics of these transformers:
P_{Fe} = 8,2 kW for T11, T12 i T13

T11: R=0,5938 Ω	T12: R=0,0951 Ω	T23: R=0,0108 Ω
X=56,9057 Ω	X=0,3124 Ω	X=0,2245 Ω
S_n=31,5 MVA	S_n=21 MVA	S_n=21 MVA

Impedances of three transformers are derived from equivalent impedances which represent three-windings transformer. Therefore, this model is a correct representation and gives voltage drops and losses as for a real three-windings transformer.

CONCLUSION

For use of software PRAO it's necessary to have accurate and precise data about existing MV grid, it's topology and characteristics. That requires a lot of time for acquisition and enter of all data needed for calculations.
Optimization of supply boundaries, simulation of fault with supply restoration possibilities, calculation in every year of the planning period taking into account technical constraints (overload on grid elements, voltage drop, Joule losses) are some of the functions that software performs.
Software PRAO is useful tool for planning and analysis in detail of 10 kV grid and also for quick calculation of implementation effects of different works on the grid. Which work is the most profitable and in which year can be determined based on defined technical criteria and economic aspects. If analysis includes several voltage levels (10 kV and 35 kV), some modifications have to be done but it's possible to obtain good results for directions of MV grid development on a certain consumer area. Comparison of total sum of all costs in different strategies gives technical and economical optimal variant of grid development.

LITERATURE

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