RIGA TECHNICAL UNIVERSITY

Ilze PRIEDITE

PROBLEMS AND SOLUTIONS OF CABLE LINES IN MEDIUM VOLTAGE NETWORKS

Summary of Doctoral Thesis

Riga 2013

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Power Engineering

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PROBLEMS AND SOLUTIONS OF CABLE LINES IN MEDIUM VOLTAGE NETWORKS

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Doctoral Thesis is proposed for achieving Dr.sc.ing. degree and will be publicly defended, at 14:00 on the 9th of January, year 2014, at Faculty of Power and Electrical Engineering of Riga Technical University,1 Kronvalda bulv., in 117. room.

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CONFIRMATION STATEMENT

Hereby I confirm that I have worked out the present Doctoral Thesis, which is submitted for consideration at Riga Technical University for achieving Dr.sc.ing. degree. This work has not been submitted to any other University for achieving scientific degree.

Ilze Priedīte …………………………….(Signature)

Date: ………………………

The Doctoral Thesis is written in Latvian language, it contains introduction, 4 chapters, conclusions and recommendations for further work, list of references, 13 tables and 64 figures, total number of pages is 110. The list of references includes 85 sources of information.

Contents

Topicality of the work

Currently is being continued DSO „Sadales tikls” 230 million investment program for approximately 6000km long OHL in forests replacment with 20 kV CL launched in 2011. It is planned to implement during 35 years and now has been developed investment plan for the first five years (see Tab. 1). [4]

Tab.1

The planned quantity and costs of cable within the 35-year program in the first 5 years [4]

Year	2011	2012	2013	2014	2015
milion LVL	1,5	3,8	5,8	7,7	7,7
km	39	100	150	200	200

Increasing the cable sections in the OHL (due to DSO "Sadales tikls" launched investment program) correct selection of thermally resistant cable becomes more difficult due to double earth faults. The double earth fault current flows through the medium voltage cable metal sheath which overheats and thus causes premature aging of outer PE jacket. One of the thesis chapters is devoted to the study of outer PE jacket ageing.

OHL replacing to CL in medium voltage network (thereby forming mixed networks), it is essential to choose properly neutral grounding type because OHL and CL have different requirements for neutral grounding, i.e., in case of CL fault is lasting therefore those should be turned off immediately, but the OHL failure can be both lasting and temporary and therefore in those power lines are recommended automatic reclosing devices. Network security and construction costs are directly dependent on neutral point connection. The correct selection of neutral point connection reduces the number, duration and the risk of a double ground fault, as well as cable insulation does not degrade prematurely. Therefore there is a great need for easy to use neutral point connection selection algorithm that would allow engineers to choose the optimal neutral point connection, thus increasing network reliability and electrical safety.

In relation to the construction cost of the cable there is the myth that CL are very expensive and therefore in rural areas can be used only in exceptional circumstances. This myth maintains and supports foreign studies. For instance, according to the Florida Power & Light Company (FPL) data, CL construction costs are 5 to 15 times more expensive than OHL (in urban areas, under roads, and hard soils, such as granite, stones, etc. costs is more expensive than in open, easily accessible, areas without trees, such as meadows shrubs, agricultural land) but COHL construction costs are construction costs are 10 to 20% more expensive than OHL.

Result of a study in Finland show that the cables in rural areas centre and industrial areas are about 30% more expensive in comparison to COHL. Results of a study in Britain summarized in the table.[27, 29]

Tab. 2.

CL costs relative to OHL [27, 29]

Voltage [kV]	Based on construction costs	Based on the life-cycle costs
11kV	1-2	1
20kV	1.2-1.5	1
33kV	2.5-3	1.4
66kV	3	1.5

From these foreign research is obvious that the construction of the cable in each country is different, because each country has a different geographical and geological structure. Researches of other states cannot be used in Latvia as the construction CL in Latvian sandy pine forest is much cheaper than in the Finnish granite rocks. That is why at the present is acute need for algorithm for economic evaluation of different line type (CL, OHL and COHL). Such algorithm enables carry out a comparative calculation to decide which one of line type is the most economical and not only from the perspective of construction costs, but also from the perspective of maintenance and repairs costs.

In Latvia until 2011 earthing system was designed and created according to LEK 048 with standardized exhaust resistance of earthing system. In 2011 was accept new LVS EN50522. Unfortunately there was not a method for MV substation earthing system calculation in this new standard. Thus, it is absolutely necessary to develop method for touch voltage calculation in MV networks in case of earth fault taking into account earth fault current return to the supply centre through medium-voltage cables metal screens, repeated earth electrodes in 0.4 kV network and also galvanically connected network earthing system of transformer substation.

Objective and tasks of the doctoral thesis

The tasks and objectives of doctoral thesis are:

1. Carry out studies of regularities in cable outer PE jacket aging.
2. Develop different types of medium voltage lines (OHL, COHL and CL) cost estimation algorithm.
3. Develop algorithm of optimal line type selection based on economic considerations.
4. Develop method for touch voltage calculation in MV networks in case of earth fault taking into account earth fault current return to the supply centre through medium-voltage cables metal screens, repeated earth electrodes in 0.4 kV network and also galvanically connected network earthing system of transformer substation.
5. Determine repeated earth electrode impedance impact on the touch voltage value.
6. Determine PEN conductor impedance impact on earthing system impedance.
7. Develop an algorithm of neutral selection and verification by touch voltage.

Methodology of research

1. Analysis of literature and research results of the cable outer polyethylene (PE) jacket destruction, uses of different neutral type, tupe of power failure and etc.
2. Experiments using a differential scanning calorimeter (DSC) in order to determine cable outer jacket melting process start temperature and using a heating furnace in order to determine cable outer jacket thermal stability for prolonged time.
3. EXCEL un MathCAD for economical, cable outer PE jacket temperature and touch voltage calculations.

Scientific importance of the Doctoral Thesis

The scientific importance of doctoral thesis is:

1. Studies were performed for regularities in cable outer PE jacket aging.
2. Elaborated cost estimation algorithm for different types of medium voltage lines (OHL, COHL and CL).
3. Elaborated method for touch voltage calculation in MV networks in case of earth fault taking into account earth fault current return to the supply centre through medium-voltage cables metal screens, repeated earth electrodes in 0.4 kV network and also galvanically connected network earthing system of transformer substation.
4. Elaborated an algorithm of neutral selection and verification by touch voltage.
5. Determined repeated earth electrode impedance impact on the touch voltage value.
6. Determined PEN conductor impedance impact on earthing system impedance.

Practical value of the Doctoral Thesis

Practical value of the doctoral thesis:

1. Performed studies for regularities in cable outer PE jacket aging is useful for distribution network exploitation engineers when using cables.

2. Elaborated cost estimation algorithm for different types of medium voltage lines (OHL, COHL and CL) allows quick and easily compare and evaluate construction, maintenance and repairs costs of different types of line depending on what kind of environment distribution line is located (a stretch of woods or under asphalt) and also depending on whether funds the line is constructed-on the company's internal or external funds.
3. Elaborated method for touch voltage calculation in MV networks in case of earth fault taking into account earth fault current return to the supply centre through medium-voltage cables metal screens, repeated earth electrodes in 0.4 kV network and also galvanically connected network earthing system of transformer substation is very useful for distribution network exploitation engineers because it allows easily and quickly perform calculations for medium-voltage earthing systems of substation.
4. Determined repeated earth electrode impedance impact on the touch voltage value.
5. The obtained touch voltage values percentage change curve depending on the repeated earth electrodes impedance (30 Ω assuming as the basis) can be useful for distribution network exploitation engineers when evaluating usefulness of impedance changes in repeated earth electrode.
6. Determined PEN conductor impedance impact on earthing system impedance can be useful for distribution network exploitation engineers when evaluating PEN resistance impact on earthing system impedance.
7. Elaborated an algorithm of neutral selection and verification by touch voltage is easy to use and enables engineers to unmistakably select neutral type, thus increasing network reliability (reducing the number of single-phase fault, duration and a double earth fault risk) and to optimize the costs of network construction.

Approbation of the Doctoral Thesis

The results obtained in the frames of development of the thesis were reported and discussed at 9 international conferences:

1. J. Rozenkrons, V. Sults, I. Priedite. Quenching of Partial Discharges in medium voltage networks by traditional arc suppression coil // „Electric Power Quality and Supply Reliability Conference (PQ)", Institute of Electrical and Electronics Engineers (IEEE), Kuressaare, Estonia, June 16-18, 2010.- Conference Proceedings, P. 203 – 206, ISBN: 978-1-4244-6978-9
2. Ilze Priedite-Razgale, Aleksandrs Lvovs, Janis Rozenkrons. Feasibility Study of OHL Replacement with Underground Cable Lines in the MV Distribution Network, CYSENI 2012, 9th International Conference of Young Scientists on Energy Issues, May 24-25, 2012, Kaunas, Lithuania, ISSN 1822-7554, (referred in INSPEC database).
3. Ilze Priedite-Razgale, Janis Rozenkrons. Development of the algorithm and software "MVES-TV 2012" for calculation of touch voltage in MV networks with low resistance neutral earthing, EPE 2012,13th International Scientific Conference on Electric Power engineering, May 23–25, 2012, Brno, Czech Republic, ISBN 978 - 80 - 214 - 4514 – 7 (Conference Proceedings Citation Index CPCI on ISI Web of Knowledge)
4. Ilze Priedite-Razgale, Janis Rozenkrons. Development of the Algorithm and Software "MVES-GS 2012" for Selection of the Neutral Grounding Type in Medium Voltage Networks, ERD 2012, 11th International Scientific Conference Engineering for Rural Development proceedings, Vol 11, May 24-25, 2012, Jelgava, Latvia, ISSN 1691-5976, page 511-515 (ABSTRACTED AND INDEXED: AGRIS; CAB ABSTRACTS; CABI full text; EBSCO Academic Search Complete; Thomson Reuters Web of Science; Elsevier Scopus; PROQUEST database)
5. Ilze Priedite-Razgale, Aleksandrs Lvovs, Vilnis Kreslins. Analysis and Comparison of Distribution System Costs, Dependant on Cable and Overhead Lines' Fault Probabilities and Maintenance Cost Difference, PMAPS` 2012, 12th International Conference on Probabilistic Methods Applied to Power Systems, June10-14, 2012, Istanbul, Turkey (published in IEEEXplore)

6. Ilze Priedite-Razgale, Janis Rozenkrons. Development of the Algorithm and Software “MVES-TV 2012” for Assessment of Touch Voltage in MV Networks with Compensated Neutral Earthing, PQ2012, 8th International Conference 2012 Electric Power Quality and Supply Reliability, June16-18, 2012, Tartu, Estonia (published in IEEEXplore)
7. Aleksandrs Lvovs, Ilze Priedite-Razgale, Janis Rozenkrons, Vilnis Kreslins. Assessment of Different Power Line Types` Life-time Costs in Distribution Network From Reliability Point of View, PQ2012, 8th International Conference 2012 Electric Power Quality and Supply Reliability, June16-18, 2012, Tartu, Estonia (published in IEEEXplore)
8. Ilze Priedite-Razgale, Jānis Rozenkrons. Development of an Algorithm and Software “MVES-TV2012” for Touch Voltage Calculation in MV Networks. Riga Technical University 53rd International Scientific Conference and the 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni, October 10-12, 2012, Riga, Latvia.
9. Ilze Priedite-Razgale, Juris Bitenieks. Single phase earth fault impact on underground cable outer PE jacket in MV isolated neutral systems, EPE 2013,14th International Scientific Conference on Electric Power engineering, May 28–30, 2013, Jeseniky, Czech Republic, (Conference Proceedings Citation Index CPCI on ISI Web of Knowledge)

Publications

The results obtained in the frames of development of the thesis are includes in 10 publications in international proceedings:

1. J. Rozenkrons, V. Sults, I. Priedite. Quenching of Partial Discharges in medium voltage networks by traditional arc suppression coil // „Electric Power Quality and Supply Reliability Conference (PQ)”, Institute of Electrical and Electronics Engineers (IEEE), Kuressaare, Estonia, June 16-18, 2010.- Conference Proceedings, P. 203 – 206, ISBN: 978-1-4244-6978-9
2. Ilze Priedite-Razgale, Aleksandrs Lvovs, Janis Rozenkrons. Feasibility Study of OHL Replacement with Underground Cable Lines in the MV Distribution Network, CYSENI 2012, 9th International Conference of Young Scientists on Energy Issues, May 24-25, 2012, Kaunas, Lithuania, ISSN 1822-7554, (referred in INSPEC database).
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10. Ilze Priedite-Razgale, Jānis Rozenkrons. Development of an Algorithm and Software “MVES-TV2012” for Touch Voltage Calculation in MV Networks. RTU Zinātniskie raksti, Enerģētika un elektrotehnika 31. sējums, sērija 4. – RTU, Rīga, 2013. – 79.-85.lpp.(ISSN 1407-7345).

Structure and volume of the thesis

The Doctoral Thesis is written in Latvian language, it contains introduction, 4 chapters, conclusions and recommendations for further work, list of references, 13 tables and 64 figures, total number of pages is 110. The list of references includes 85 sources of information.

1. Research of ageing regularities in the medium voltage underground cable outer PE jacket

In this chapter are analysed causes of the cable outer PE jacket heating, carried out assessment of cable outer PE jacket physicochemical properties, analysed destruction of cable outer PE jacket and also carried out cable outer PE jacket thermal stability test with DSC.

Increasing the cable sections in the OHL (Latvian DSO "*Sadales tīkls*" launched 230 million investment program [4]) will become more topical a variety of problems including problems associated with the earth faults. In case of double earth fault a large part or even the whole fault current flows through the screen and is heating insulation and outer PE jacket.

This thesis chapter is devoted to research of ageing regularities in the cable outer PE jacket. Warming of the cable outer PE jacket is dependent on the network operation mode, i.e., warming in case of normal load, warming in case of single earth fault and warming in case of double earth fault. There is no automatic, fast disconnection of earth fault current in medium voltage cable networks with isolated neutral. According to studies carried out in some 20kV networks, single-phase earth fault current can reach up to 100A.

Simplified process of cable outer jacket destruction shown in Fig. 1.1. [13]

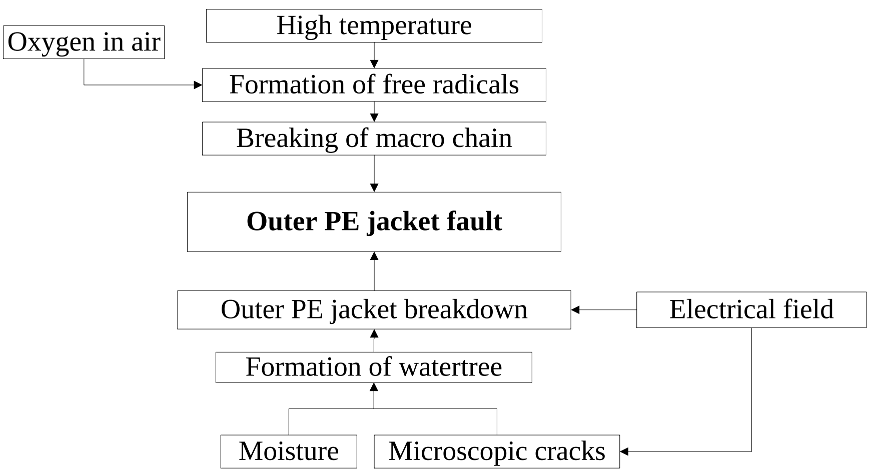

Fig.1.1. Process of cable outer PE jacket destruction [11, 13]

The cable outer PE jacket thermal stability analysis was performed by using Mettler Toledo differential scanning calorimeter DSC 1, under a constant flow of nitrogen and a heating rate of

10°C/min from ambient temperature 25^{0}C to 300ºC (for some samples 25^{0}C to 380ºC) in RTU Institute of Polymer Materials. DSC allowed estimating the 12 XLPE insulated cable outer PE jacket crystalline phase melting behaviour (melting peak maximum temperature T_{m1}, melting temperature range ΔT_{m1}). These parameters were determined using the original program METTLER GraphvVare TA72PS.5.

In this study 6 single-core and 6 three-core XLPE cables with different duration of operation, voltage and manufacturer from Latvian DSO, were analyzed. Samples of PE (~9.5mg) were encapsulated in a standard aluminum pan. For all these cables in technical specification it is stated that the maximum conductor temperature in continuous operation is 90°C (recommended for use is only 65°C) but maximum safe temperature in a short circuit is 250°C (for time shorter than 5 seconds). [30, 7, 12]

Cable outer PE jackets are made from the different density polyethylene with different additives. Therefore, the melting temperature ranges are different, i. e, a crystalline polymer melting temperature occurs in the temperature range. By temperature range it possible to determine the degree of crystallinity of the polymer and the level of orderliness of crystal structure (less arranged in crystalline formations melts at a lower temperature). It is possible to identify the purity of the material by DSC curves, as shown in Fig. 1.2. [21]

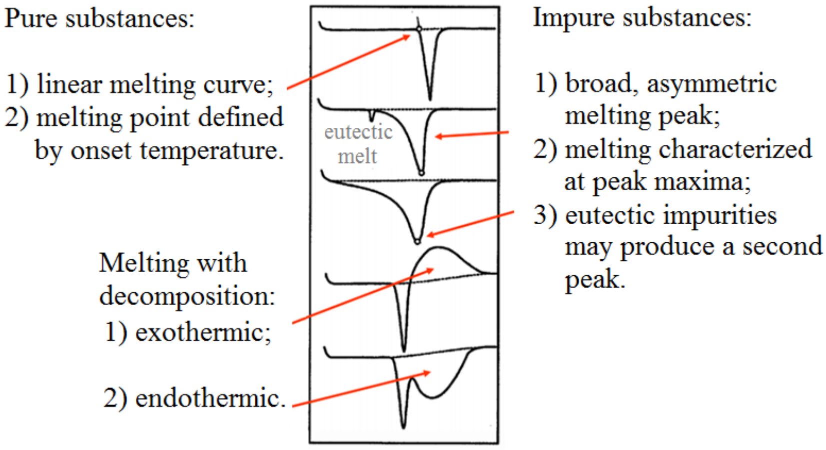

Fig.1.2. Melting processes by DSC [21]

Figure 1.3 shows dynamic DSC thermogram of the sample No.5. As one can see broad multipeak melting behaviour in the temperature interval from 42°C to 121°C is characteristic for this material. A maximum of the melting peak is observed at the temperature of 109.74°C. Besides it two additional overlapping melting peaks can be observed at lower temperatures, i.e. at 91.46°C and 61.02°C, testifying about multi-component nature of the material. Thermal decomposition of the material can be clearly observed at 238.23°C.

According to the literature, the melting temperature of low density PE is around 98…115°C, medium-density 122…124°C, but high-density PE 130…137°C. [13, 17] Considering this, the main component of the samples No.7 and No.5 most probably is low density PE, while the main component of the samples No.6 and No.8 most probably is medium-density PE. Main component of the samples No.1 and No.11, showing no remarkable melting peak, most probably is some polyethylene copolymer with low crystallinity degree.

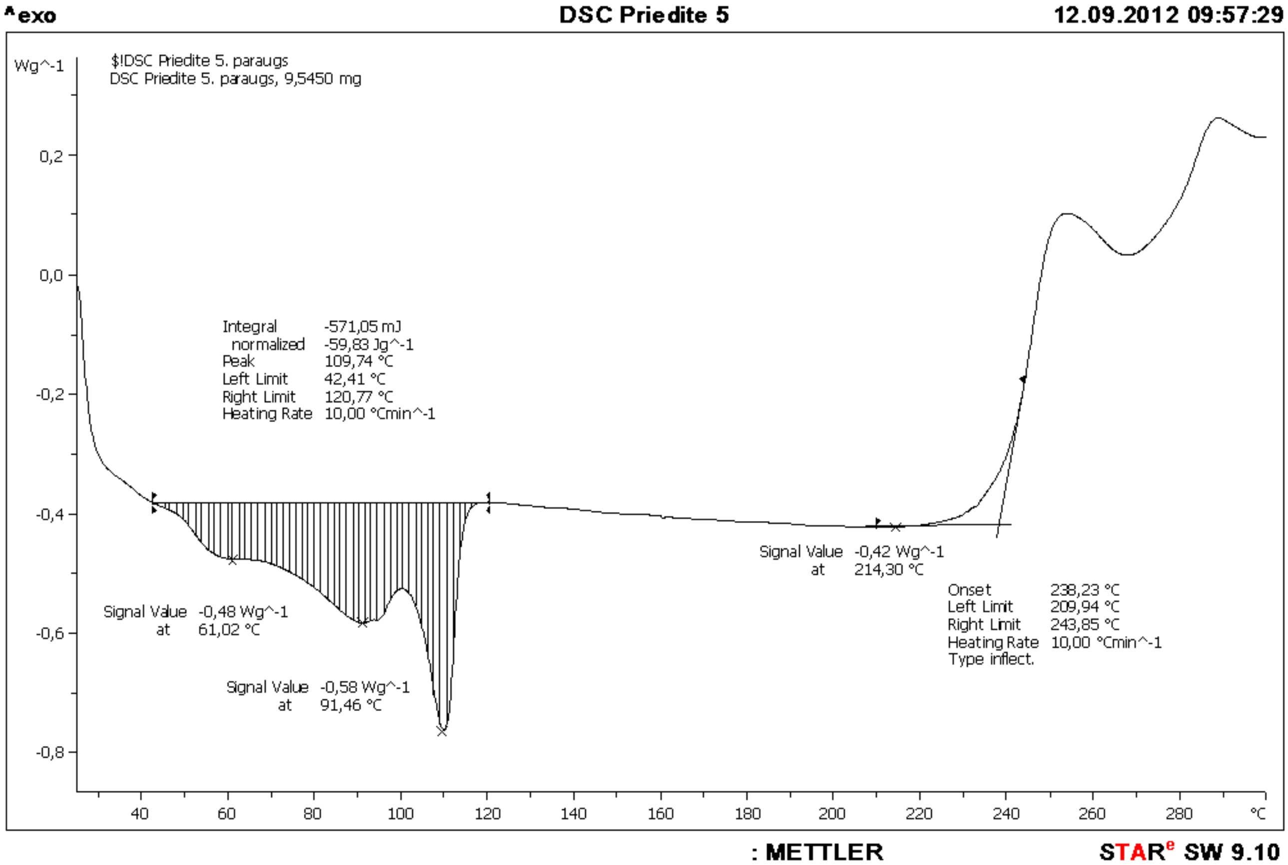

Fig.1.3. DSC thermogram of sample Nr. 5

Results of tested single-core XLPE cables outer PE jacket are summarized in the Tab.1.1.

Tab.1.1.

Results of tested single-core XLPE cables outer PE jacket

Sample No.	Voltage, KV	Outer PE jacket	Duration of operation, years	Melting process start temperature, °C	Maximum melting peak temperature, °C	Temperature of thermal decomposition of the material, °C
1	10	PE UV-resistant	2007[a]	-*	-*	280.64
7	10	PE DMP2	12	57.69	85.76	310.66
5	20	PE compound	5	42.41	109.74	238.23
11	20	PE compound	6	-*	-*	278.14
6	20	PE weather resistant	6	53.45	120.05	275.53
8	20	PE weather resistant	6	44.12	124.09	267.77

[a] year of manufacture (unused cable from warehouse)

* Melting of the crystalline part of the material is negligible, it is likely to be due to the amorphous nature of the material.

Results of tested three-core XLPE cables outer PE jacket are summarized in Table 1.2.

Results shows that the main component of the samples No. 2, No.3, No.4. and No.12 most probably is made of low density PE but the main component of sample Nr.9 most probably is made of medium or high density PE. Sample No. 10 shows no significant melting, thus most probably it is made of polyethylene copolymer or some other rubbery material with low crystallinity degree.

Tab. 1.2.

Results of tested three-core XLPE cables outer PE jacket

Sample No.	Voltage, KV	Outer PE jacket	Duration of operation, years	Melting process start temperature, °C	Maximum melting peak temperature, °C	Temperature of thermal decomposition of the material, °C
2	20	PE	4	53.44	103.50	268.45
3	10	PE	3	56.91	97.75	286.02
4	10	PE	3	34.54	94.80	290.57
9	10	PE	2011[a]	76.36	126.08	268.61
10	10	LLD PE	2012[a]	268.37	334.76	268.37
12	10	PE	11	57.77	106.22	270.65

[a] year of manufacture (unused cable from warehouse)

The results shows that it is not possible obtain the regularities of aging for cable outer PE jacket like regularities of aging for impregnated paper insulated cables (6°C degree increases doubly insulation ageing) because cable outer PE jacket are not made of pure polyethylene. Each cable outer PE jacket material is made of various densities polyethylene with different additives (antioxidants, flame retardants, plasticizers, stabilizers, etc.), which so much changes physical and chemical properties of this material that they are not comparable with each other. Hence aging regularities would be possible obtain only by a specific manufacturer's specific cable brand.

Practically it would mean that each manufacturer of each cable brand research should be given 30-40 years to assess how in these 30-40 years have changed this specific manufacturer's specific brand of cable outer PE jacket. It is time and resource intensive study which usefulness is questionable due to the continuous development of new cable outer PE jacket compounds whose properties differ significantly from the previously manufactured.

2. Algorithm for optimal line type (OHL, CL, COHL) selection based on economic considerations

In this chapter analysed the construction, operation and fault elimination costs for different line type constructions, proposed algorithm for selecting optimal type of line based on economic consideration as well as the calculation example.

There is a myth about cable costs -that they are very expensive and therefore should be used only in exceptional circumstances. This myth maintains and supports foreign studies. For instance, according to the Florida Power & Light Company (FPL) data, CL construction costs are 5 to 15 times more expensive than OHL (in urban areas, under roads, and hard soils, such as granite, stones, etc. costs is more expensive than in open, easily accessible, areas without trees, such as meadows shrubs, agricultural land) but COHL construction costs are construction costs are 10 to 20% more expensive than OHL.

Results of a study in Finland shows that the cables in rural areas centre and industrial areas are about 30% more expensive in comparison to COHL. Results of a study in Britain summarized in the 2.1. table. [27, 29]

Tab. 2.1.

CL costs relative to OHL [27, 29]

Voltage [kV]	Based on construction costs	Based on the life-cycle costs
11kV	1-2	1
20kV	1.2-1.5	1
33kV	2.5-3	1.4
66kV	3	1.5

From these foreign research is obvious that the construction of the cable in each country is different, because each country has a different geographical and geological structure. Researches of other states cannot be used in Latvia as the construction CL in Latvian sandy pine forest is much cheaper than in the Finnish granite rocks. That is why at the present is acute need for algorithm for economic evaluation of different line type (CL, OHL and COHL). Such algorithm enables carry out a comparative calculation to decide which one of line type is the most economical and not only from the perspective of construction costs, but also from the perspective of maintenance and repairs costs. Sometimes the line with higher construction costs turns out less expensive than the lines with lower construction costs, if viewing all life cycle of line.

Total annual costs for each type of line during its entire life cycle is the sum of all three lines life-cycle stages - construction, operation and fault elimination costs according to equation 2.1. [14]:

$$C = C_i + C_{mi} + C_{f.e.i} \tag{2.1}$$

kur C_i – total construction costs of lines with parameters *i* [monetary units];
C_{mi} – total preventive repair/maintenance costs of lines with parameters *i* [monetary units];
$C_{fe.i}$ – total fault elimination costs for lines with parameters *i* [monetary units];

Operating costs, as well as construction and repairs costs for each line type is different, so each of them this cost type should be calculated with the appropriate equation for particular line type.

For instance, the OHL and COHL operating costs should be calculated according to equation (2.2.) [20]:

$$C_{mi} = N_i \cdot (C_{org} + C_{op.s} + C_m) \cdot \frac{l_i}{100} + l_i \cdot 1000 \cdot l_{pzi} \cdot C_{cpz} \cdot \frac{1}{p_{cpz}}, \tag{2.2}$$

kur N_i – number of preventive repair works during 1 year [monetary units/(km*year)];
C_{org} – work organizing costs [monetary unit/preventive repair work];
$C_{op.s}$ – costs of operative switchings [monetary unit/switching];
C_m – costs of materials used during one preventive repair [monetary units /repair];
l_i –length of lines with parameters *i* [km];
$l_{pz.i}$ – total protective zone length (to both sides of line) of lines with parameters *i* (in Latvia for OHL up to 20kV is 2x6.5=13m; according to [6]) [m];
C_{cpz} – protective zone maintenance costs [monetary unit/m^2];
p_{cpz} – time interval between protective zone maintenance works [years].

In turn CL operating costs should be calculated according to equation 2.3. [20]:

$$C_{mi} = \frac{l_i \cdot 1000 \cdot l_{pz.i} \cdot C_{cpz}}{p_{cpz}}, \tag{2.3.}$$

where l_i – length of lines with parameters *i* [km];
$l_{pz.i}$ – total protective zone length (to both sides of line) of lines with parameters *i* (in Latvia for underground cable line 2x1=2m – according to [6]) [m];
C_{cpz} – protective zone maintenance costs [monetary unit/m^2];
p_{cpz} – time interval between protective zone maintenance works [years].

Not always the optimal type of line in each case is only one type of line. This is due to the fact that often one line route located in different environments such as forest, meadow (shrubs, agricultural land), below the asphalt etc. For that reason sometimes the optimal solution is combination of several line types depending on the environment in which the line passes.

Costs of several line type combination should be calculated according to equation 2.4.[20]:

$$C = \sum_{i=1}^{n} (C_i + C_{mi} + C_{fe.i}) \tag{2.4}$$

where C – [monetary units/time period];
C_i – total construction costs of lines with parameters *i* [monetary units];

C_{mi} – total preventive repair/maintenance costs of lines with parameters *i* [monetary units];
$C_{fe.i}$ – total fault elimination costs for lines with parameters *i* [monetary units];
i – number, corresponding to power line with specific parameters;
n – total number of lines with different parameters used for the network.

Construction costs also depend on whether the network development project will be carried out - by the company's internal financial resources (such as savings from the fault elimination financial resources if during the year has been less damage than expected, etc.) or external financial resources (e.g., bank credit). If the construction is performed using external financial resources then calculated construction cost should be adjusted using the NPV (Net Present Value) method. Thereby calculation takes into account the bank credit interest rate, inflation rate and the lending period. Construction cost should be adjusted according to 2.5. equation [14]:

$$C_i = \frac{C_{1kmi} \cdot l_i \cdot \left(1 + \frac{\text{int}_r}{100}\right)^{t_{cr}}}{\left(1 + \frac{\text{inf}}{100}\right)^{t_{cr}} \cdot t_{ei}}, \tag{2.5}$$

where C_{1kmi} – construction costs of lines with parameters *i* [monetary units / km];
l_i – length of lines with parameters *i* [km];
int_r – interest rate [%];
t_{cr} – time of credit [years].
inf – inflation [%];
t_{ei} – exploitation time (life time) of lines with parameters *i* [years].

Different types of medium voltage lines (OHL, COHL and CL) cost estimation algorithm shown in Figure 2.3.

Calculation example for the construction of new lines based on cost data Latvian [32].

To compare the OHL, COHL and CL costs the calculation is carried out on three separate occasions- the case in which the entire network is constructed of OHL, in case in which the entire network is constructed of COHL, and in case in which the entire network is constructed of CL.

In all cases, OHL, COHL and CL are selected so that they ensure the carrying capacity required for the network which is under consideration.

Existing OHL line replacement with CL or COHL whole lifetime costs in rural areas without rigid pavements streets, assuming that half of the lines length is located forest and half of lines length in the agricultural (grassland, bush) land (construction using only the company's internal financial resources) results shown in Fig. 2.1.

The calculation results show that CL has the largest construction and fault elimination costs but COHL has almost two times smaller costs than CL. However, operating costs has opposite character- COHL costs are more than 8 times higher than the CL costs. Whole lifetime costs in this case are almost identical, but for COHL these costs are a little bit lower than CL costs.

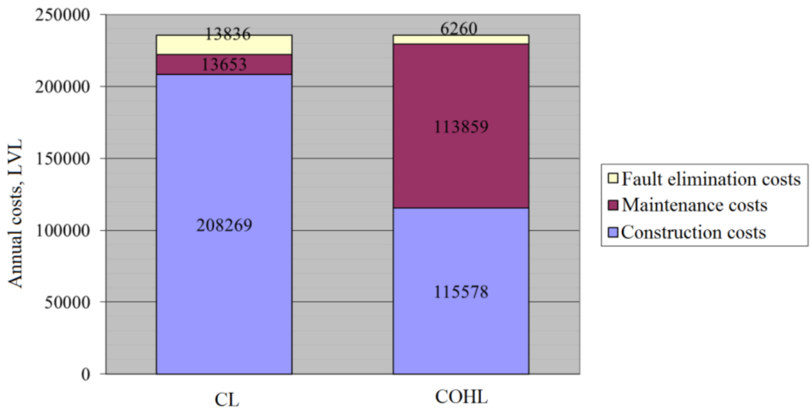

Fig.2.1. Existing OHL line replacement with CL or COHL whole lifetime costs in rural areas without rigid pavements streets, assuming that half of the lines length is located forest and half of lines

length in the agricultural (grassland, bush) land (construction using only the company's internal financial resources)

The calculation results show that CL has the largest construction and fault elimination costs but COHL has almost two times smaller costs than CL. However, operating costs has opposite character-COHL costs are more than 8 times higher than the CL costs. Whole lifetime costs in this case are almost identical, but for COHL these costs are a little bit lower than CL costs.

Existing OHL line replacement with CL or COHL whole lifetime costs in rural areas without rigid pavements streets, assuming that half of the lines length is located forest and half of lines length in the agricultural (grassland, bush) land (construction using only the company's external financial resources) calculation results shown in Fig.2.2.

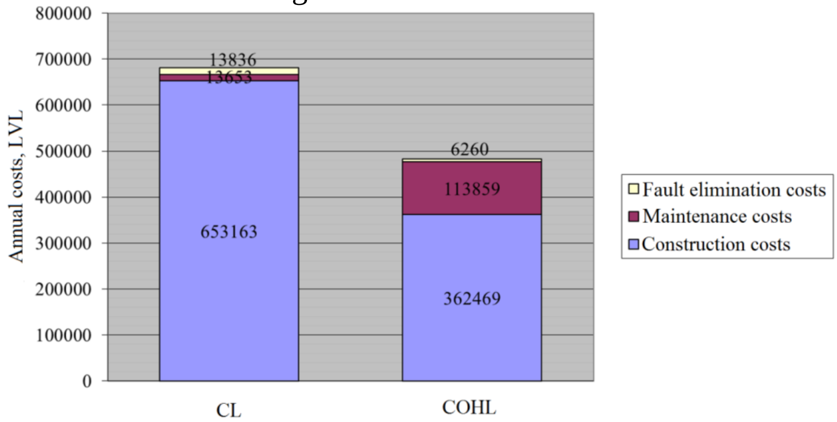

Fig. 2.2. Existing OHL line replacement with CL or COHL whole lifetime costs in rural areas without rigid pavements streets, assuming that half of the lines length is located forest and half of lines length in the agricultural (grassland, bush) land (construction using only the company's external financial resources)

The calculation result shows that CL has the biggest construction and repairs costs, but COHL has significantly smaller costs than the CL.

However, operating costs has opposite character-COHL costs are more than 8 times higher than the CL costs. COHL whole lifetime costs are the smallest in this case.

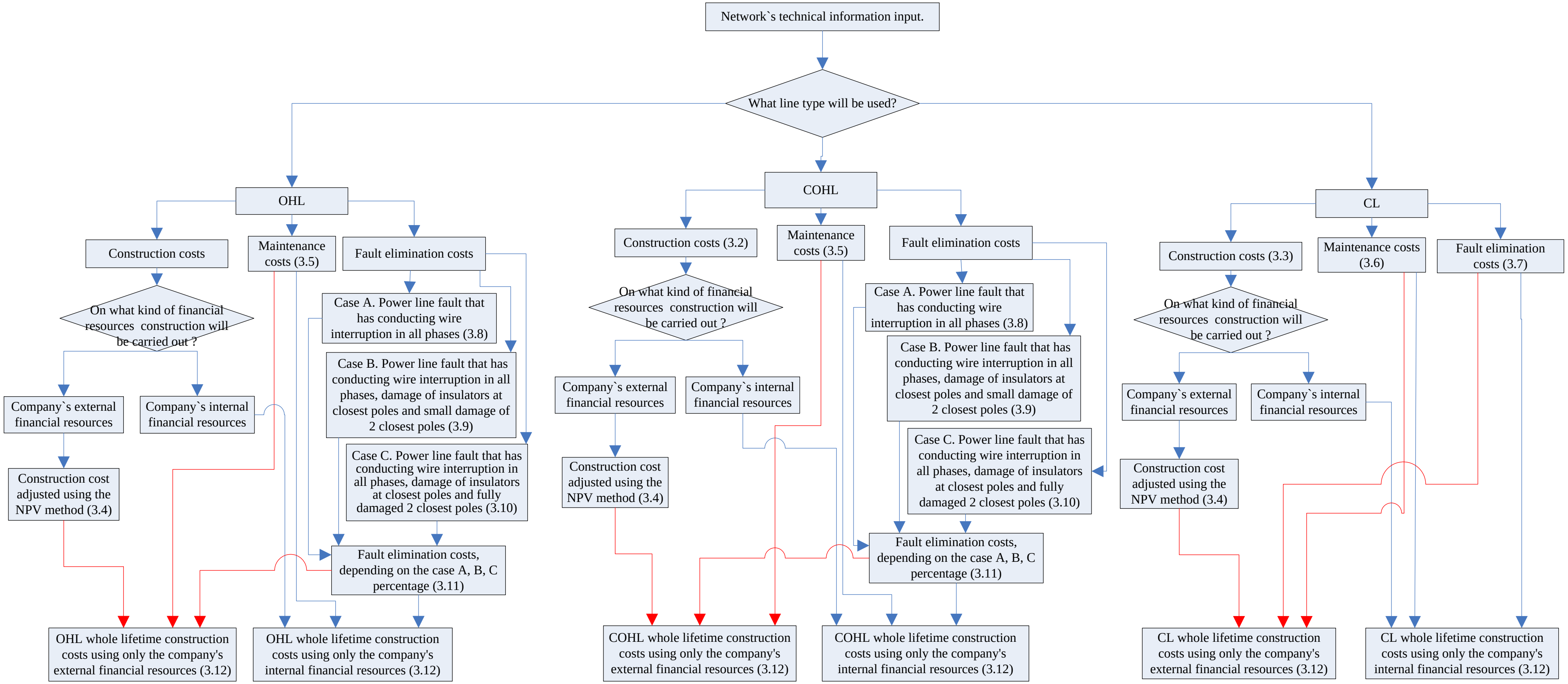

Fig 2.3. Different types of medium voltage lines (OHL, COHL and CL) cost estimation algorithm (brackets used in the algorithm`s diagram correspond to equation numeration in doctoral thesis

3. Method for touch voltage determining of earth fault in medium voltage networks

In this chapter is offered method for touch voltage determining in case of earth fault, assessed repeated earth electrode impedance impact on touch voltage value as well as the PEN impedance impact on earth electrode impedance.

In Latvia until 2011 earthing system was designed and created according to LEK 048 with standardized exhaust resistance of earthing system. In 2011 was accept new LVS EN50522. Unfortunately there was not a method for MV substation earthing system calculation in this new standard. Therefore in frame of promotion work has been taken participation in new LEK 136 “MV network neutral operation modes (isolated, compensated and low resistive neutral)” creation in order to establish the calculation method for medium-voltage substation earthing system.This method is designed for the touch voltage determining in MV networks in case of earth fault taking into account earth fault current return to the supply centre through medium-voltage cables metal screens, repeated earth electrodes in 0.4 kV network and also galvanically connected network earthing system of transformer substation. [15, 31, 28]

Earth fault current, erthing system current, current via the resistance to earth of the mesh earth electrode, earth potential rise, repeated impedance to earth, resistance to earth of the mesh earth electrode, impedance of natural earth electrode of transformer substation, etc. shown in Fig.3.1.

Substitution scheme in case of earth fault in earthing system area of distribution transformer shown in Fig.3.2. Substitution scheme takes into account the repeated earth electrode impedance, resistance to earth of the mesh earth electrode, impedance of natural earth electrode of transformer substation, current via the resistance to earth of the mesh earth electrode, impedance of adjacent transformer earth electrode.

Touch voltage value should be determined and its permissibility assessed by Energy Standard LEK 136 and the national standard LVS EN50522: 2011 instructions. [23, 15, 25]

Earthing system current according to the calculation methodology "Touch voltage and permissible earthing circuit exhaust resistance determination in medium voltage network in case of isolated, compensated or low resistance neutral earthing", developed with the participation author of the thesis [15]:

$$I_E = r \cdot I_F \tag{3.1}$$

where I_E - current to earth;
r –reduction factor;
I_F - earth fault current.

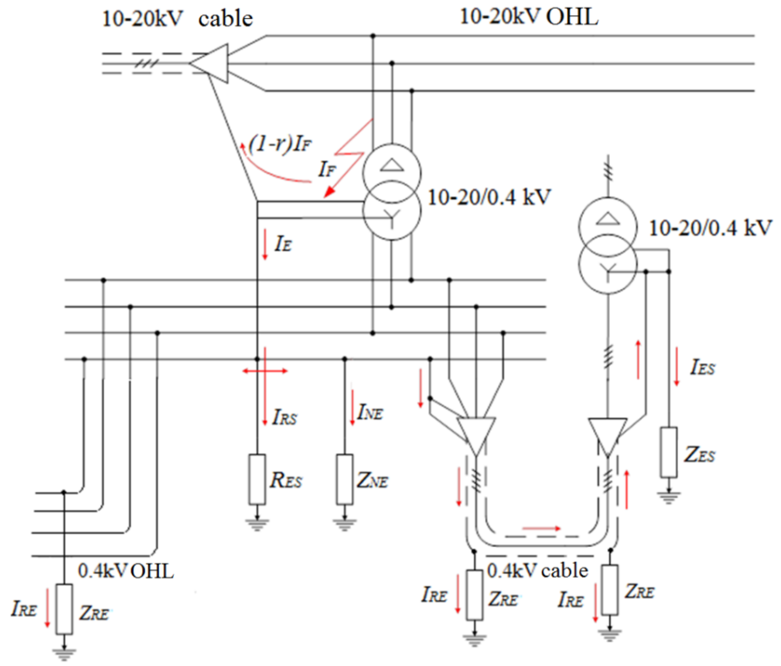

Fig. 3.1. Current, voltage and resistance in case of earth fault in area of distribution transformer earthing system *(r* –reduction factor, I_E –current to earth, I_F –earth fault current, U_E – earth potential rise, Z_{RE} - repeated impedance to earth, R_{ES}-resistance to earth of the mesh earth electrode, Z_{NE} - impedance of natural earth electrode of transformer substation, I_{RS} –current via the resistance to earth of the mesh earth electrode, Z_{ES}- impedance of adjacent transformer earth electrode) [15]

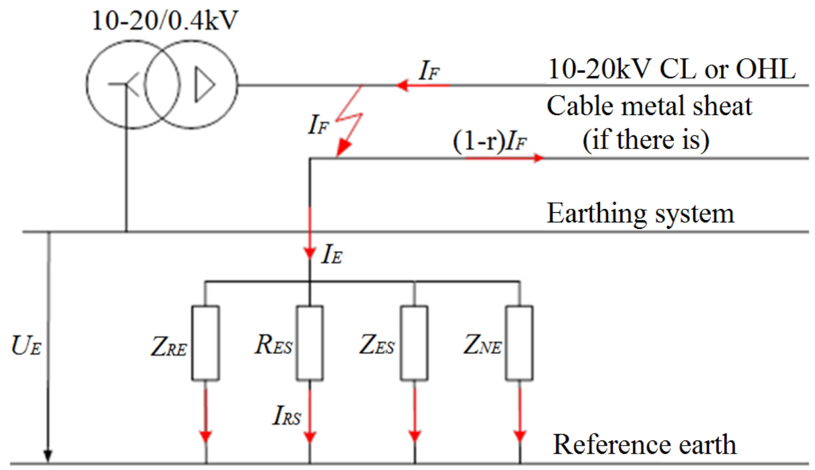

Fig.3.2. Substitution scheme in case of earth fault in earthing system area of distribution transformer *(r* –reduction factor, I_E –current to earth, I_F –earth fault current, U_E – earth potential rise, Z_{RE} - repeated impedance to earth, R_{ES}-resistance to earth of the mesh earth electrode, Z_{NE} - impedance of natural earth electrode of transformer substation, I_{RS} –current via the resistance to earth of the mesh earth electrode, Z_{ES}- impedance of adjacent transformer earth electrode) [15]

Earth potential rise [15]:

$$U_E = I_E \cdot Z_E \tag{3.2}$$

where U_E – earth potential rise;
I_E –current to earth;
Z_E- impedance to earth.

Impedance to earth[15]:

$$Z_E = \frac{1}{\frac{1}{R_{ES}} + \frac{1}{Z_{NE}} + \sum^{n} \frac{1}{Z_{ES}} + \sum^{m} \frac{1}{Z_{RE}}} \quad (3.3)$$

where Z_E- impedance to earth.

R_{ES}- resistance to earth of the mesh earth electrode,

Z_{NE} - impedance of natural earth electrode of transformer substation;

n- number of adjacent transformers;

Z_{ES}- impedance of adjacent transformer earth electrode;

m- number of repeated earth electrode;

Z_{RE} - repeated impedance to earth.

Touch voltage and distribution transformer substation earthing system verification algorithm is shown in Fig.3.3.

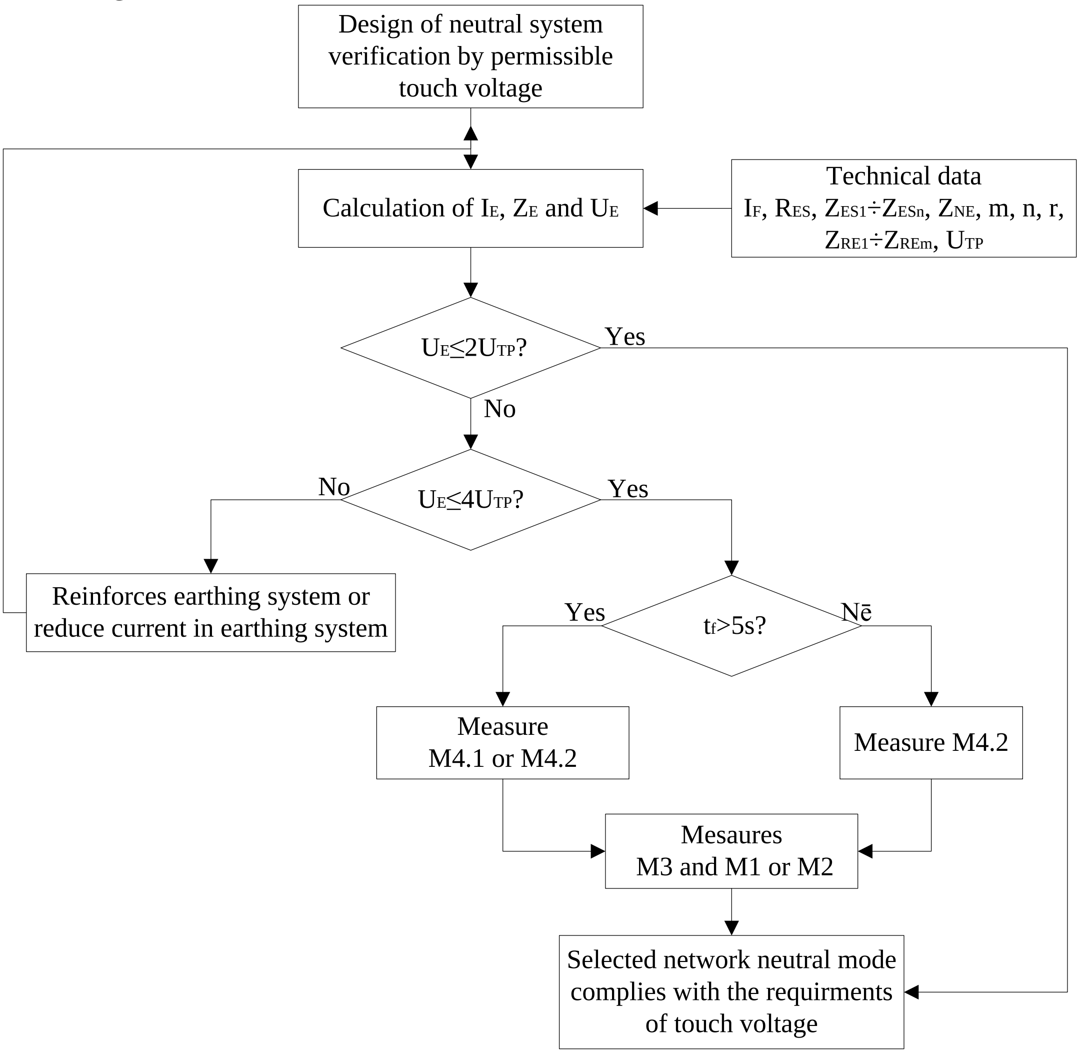

Fig.3.3. Touch voltage and distribution transformer substation earthing system verification algorithm [15]

In order to allow the U_E value $4U_{TP}$ value, should be reinforced earthing system or reduced the earthing system current, for example by increasing vertical earthing electrode number or length, installs the fourth wire in medium voltage OHL, construction of CL instead of OHL, etc. Shall then be repeated touch voltage verification [15]

To determine the repeated earth electrode impedance effects on touch voltage value was carried out touch voltage calculation at various touch voltage repeated earth electrode resistance values for 20/0.4kV distribution substation with two distribution transformers connected to the 20kV network CL with Al screen and cores.

Touch voltage values percentage change curve depending on the repeated earth electrodes impedance (30 Ω assuming as the basis) shown in Fig.3.4.

Increasing repeated earth electrode impedance by 33%, touch voltage increased by 16.49%. By doubling the repeated earth electrode impedance, touch voltage increased by 39.79%. Reducing repeated earth electrode impedance by 66%, touch voltage reduced by 22.27% while reducing repeated earth electrode impedance by 33%, touch voltage decreases by 53.40%.

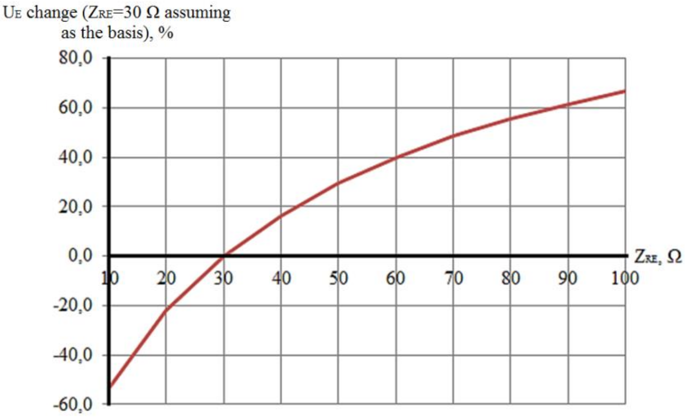

Fig.3.4. Touch voltage values percentage change curve depending on the repeated earth electrodes impedance (30 Ω assuming as the basis)

The estimated repeated earth electrode impedance impact on touch voltage value shows that by increasing repeated earth electrode impedance also increases touch voltage and vice versa.

This correlation is proportional. Touch voltage value changes is more rapidly at lower repeated earth electrode impedance value changes.

The obtained touch voltage values percentage change curve depending on the repeated earth electrodes impedance (30 Ω assuming as the basis) can be useful for distribution network operation engineers when evaluating usefulness of the repeated earth electrode impedance changes.

In order to determine PEN resistance impact on earthing system impedance was carried out earthing system impedance and touch voltage calculation of the two cases- in case where PEN resistance is taken into account and in case where PEN resistance is not taken into account. In case where PEN resistance is not taken into account was used substitution scheme shown in Fig.3.5.

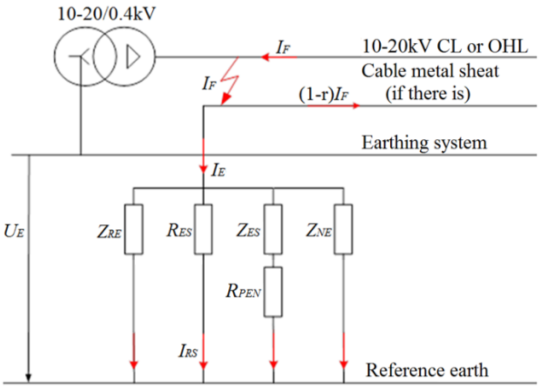

Fig. 3.5. Substitution scheme in case of earth fault in earthing system area of distribution transformer (*r* –reduction factor, I_E –current to earth, I_F –earth fault current, U_E – earth

potential rise, Z_{RE} - repeated impedance to earth, R_{ES}-resistance to earth of the mesh earth electrode, Z_{NE} - impedance of natural earth electrode of transformer substation, I_{RS} –current via the resistance to earth of the mesh earth electrode, Z_{ES}- impedance of adjacent transformer earth electrode, R_{PEN}-PEN resitance) [15]

Calculation was made 20/0.4kV distribution substation with two distribution transformers connected to the 20kV network CL with *Al* screen and cores.

Earth potential rise 20kV CL network with *Al* screen and cores, if PEN resistance is not taken into account:

$$U_E = I_E \cdot Z_E = 8.48 \cdot 0.57 = 4.83V \tag{3.4}$$

and the case in which the PEN line resistance is taken into account:

$$U_E = I_E \cdot Z_E = 8.48 \cdot 0.59 = 5V \tag{3.5}$$

So, if in the calculation is taken into account the PEN impedance, then substation earthing system impedance and touch voltage increases by 3.5%.

4. Algorithm for neutral system selection and verification by permissible touch voltage

In this chapter is analysed the neutral effect on single and double-ground fault in medium voltage network, touch voltage and neutral point connection in medium voltage network and elaborated algorithm for optimal neutral point connection selection.

Algorithm for neutral earthing system selection and verification by permissible touch voltage shown in Fig.4.1.

Optimal operating mode for neutral should start with the technical reasoned choice of the medium voltage network type- CL or OHL.

In case of OHL, mixed line and CL subsequent choice affects capacitive earth fault current value for each voltage level of the network, i.e., isolated neutral operating mode should be selected if the capacitive earth fault current in 6kV network is less than 30A, in 10kV network-less than 25A, and in 20kV network- less than 20A.

In the case where the capacitive earth fault current in 6kV network is greater than 30A, in 10kV network- greater than 25A, but in 20kV network-greater than 20A, in OHL or mixed network should be selected compensated neutral system (if bias voltage of line is more than 15% of the phase voltage, should be selected compensated neutral system with auxiliary resistor or transposition) and in CL- low resistance neutral earthing. [16, 10, 15] After neutral network operation mode selection, it is necessary to determine the permissibility of the touch voltage and earth loop permissible values. Touch voltage permissibility assess indirectly by calculating the voltage on earthing system. To do this, it is necessary to calculate the current in earthing system (I_E) earthing system impedance (Z_E) and the potential increase in earthing system (U_E). If the potential rise on earthing system is less or equal to double permissible touch voltage value then selected network neutral earthing mode complies with the requirements of touch voltage. If the potential increase in earthing system is more than twice the permissible touch voltage value, then further action will be determined by the potential increase in earthing system, i.e., if the potential increase on earthing system is more than four times than permissible touch voltage value, then should be reinforced earthing system or reduced current in earthing system and should be repeated assessment permissibility by touch voltage. If the potential rise on earthing system is less than four times permissible touch voltage value then further actions will determine the failure time (t_f), i.e., if failure time is more than 5 seconds, then provides for measures M4.1 and M4.2, but if it is less than 5 seconds, then provides for measure M4.2. In both cases requires two additional measures-M3 and M1 or M2. The measures are in detail described in 3.2. subchapter. After implementing these measures, the selected network neutral mode complies with the requirements of touch voltage.

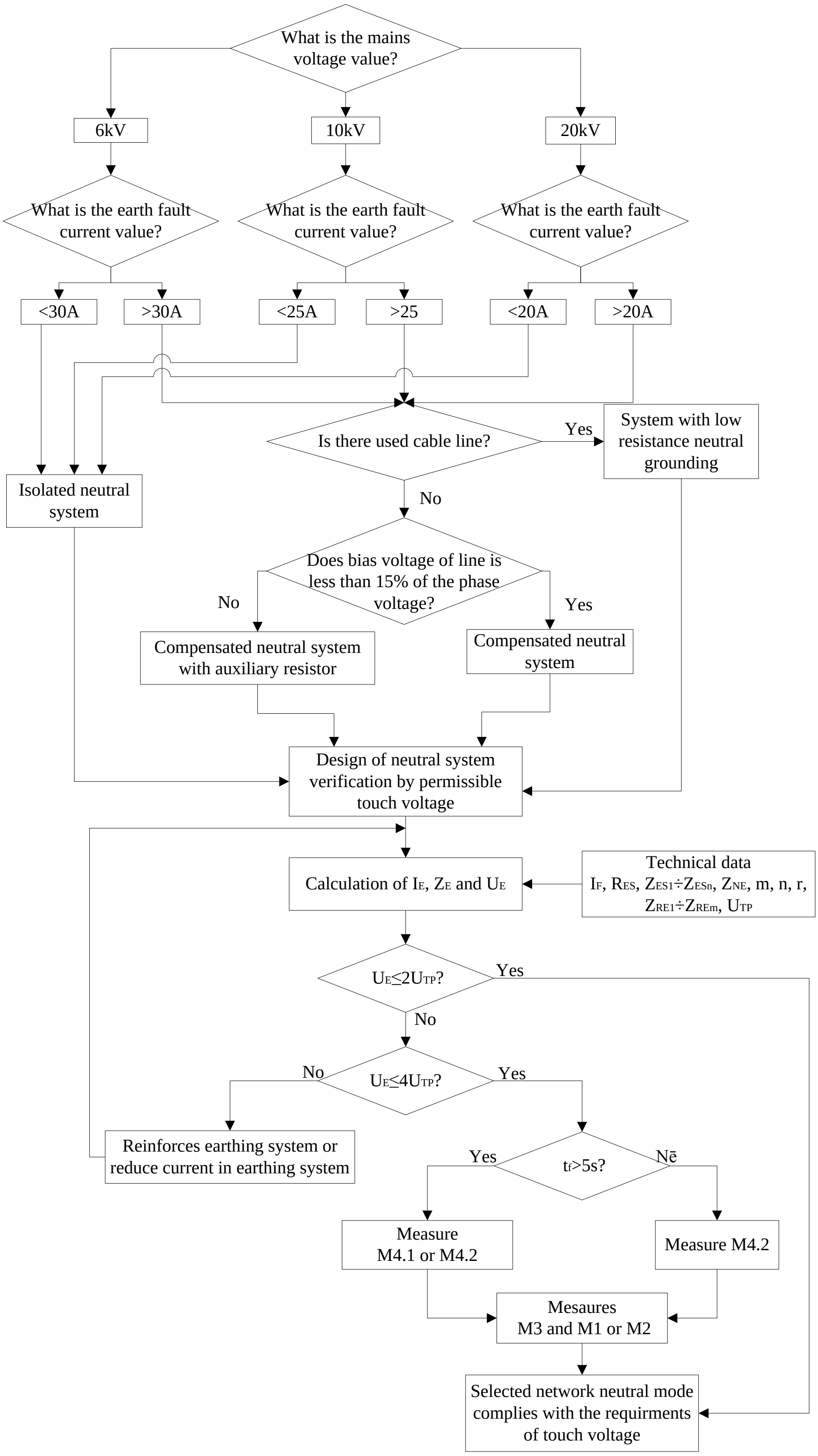

Fig.4.1. Algorithm for neutral system selection and verification by permissible touch voltage [3, 10, 15, 16]

Recognized specified measures for the outer walls of building with indoor installations. One of the recognized specified measures M 1.1. to M 1.3. may be applied as protection against external touch voltage.

M1.1: Use of non-conductive material for the outer walls (for example masonry or wood) and avoidance of earthed metal parts which can be touched from outside.

M1.2: Potential grading by a horizontal earth electrode which is connected to the earthing system at a distance of approximately 1m outside the outer wall and at a maximum depth of 0.5m.

M1.3: Insulation of the operating location: The layers of insulating material shall be of sufficient size, so that it is impossible to touch the earthed conductive parts with the hand from a location outside the insulating layer. If touching is possible only in lateral direction, an insulating layer width of 1.25m is sufficient.

M2: Recognized specified measures for external fences at outdoor installations. One of the recognized specified measures M2.1 to M2.3 may be applied as protection against external touch voltage; at gates in external fences recognized specified measure M2.4 also has to be considered.

M2.1: Use of fences of non-conductive material or of plastic-covered wire mesh (also with bare conductive slats).

M2.2: When using fences of conductive material, potential grading by a horizontal earth electrode, which is connected to the fence, at a distance of approximately 1m outside the fence and at a maximum depth of 0.5m. The connection of the fence to the earthing system is optional (however see recognized specified measure M2.4).

M2.3: Insulation of the operating location in accordance with recognized specified measure and earthing of the fence either in accordance with Annex G or by connection with the earthing system.

M2.4: If gates in external fences are connected directly to the earthing system or via protective conductors or metal sheaths of cables for staff locator systems etc., then at the opening area of the gates a potential grading or insulation of the operating location in accordance with recognized specified measure M1.3 has to be applied.

M3: Recognized specified measures in indoor installations. Within indoor installation one of the recognized specified measures M3.1 to M3.3 may be applied.

M3.1: Equipotential grading by embedding grid-type electrodes in the building foundations and connection to the earthing system at a minimum of two separate locations. If concrete steel reinforcement is also used for dissipating the fault current, the capability of the steel reinforcement shall be checked by calculation. If structural steel mats are used, then the adjacent mats have to be interconnected at least once and all the mats together have to be connected to the earthing system at a minimum of two locations. At existing buildings a horizontal earth electrode may be used, which has to be buried in the soil near the outside walls and connected to the earthing system.

M3.2: Construction of the operating locations from metal and connection to any metal parts which have to be earthed and which can be touched from the operating location.

M3.3: Insulation of the operating locations for the earth potential rise in accordance with recognized specified measures M1.3.

M4: Recognized specified measures in outdoor installations:

M4.1: At operating locations construction of the operating locations from metal and connection to the metal parts which have to be earthed and which can be touched from the operating location. Or insulation of the location in accordance with the recognized specified measure M1.3. For equipotential bonding the metal parts which have to be earthed and which can be simultaneously touched from the operating location, have to be interconnected.

M4.2: Burying a horizontal earth electrode surrounding the earthing system in the form of a closed ring. Inside this ring, a meshed earth grid has to be buried, whose individual meshes have a maximum size of 10m x 50m. [15]

Conclusions and recommendations for further work

„The border of science is like a horizon: as closer we come to it, as more it moves away"
(Pierre-Claude-Victor Boiste)

In this doctoral thesis were obtained new knowledge about cable line section problems and solutions in medium-voltage overhead line networks.

The results shows that it is not possible obtain the regularities of aging for outer PE jacket like regularities of aging for impregnated paper insulated cables (6°C degree increases doubly insulation ageing) because outer PE jacket are not made of pure polyethylene. Each outer PE jacket material is made of various densities polyethylene with different additives (antioxidants, flame retardants, plasticizers, stabilizers, etc.), which so much changes physical and chemical properties of this material that they are not comparable with each other. Hence aging regularities would be possible obtain only by a specific manufacturer's specific cable brand.

Practically it would mean that each manufacturer of each cable brand research should be given 30-40 years to assess how in these 30-40 years have changed this specific manufacturer's specific brand of cable outer PE jacket. It is time and resource intensive study which usefulness is questionable due to the continuous development of new cable polymer outer jacket compounds whose properties differ significantly from the previously manufactured.

Cable manufacturers do not always indicate of what density polyethylene cable outer PE jacket is made but it is important because thermal and physical properties is dependent on the density of the material. From the heat resistance point of view most usefully is select the cables which outer jackets made of high-density PE because its melting point is significantly higher (130 ... 137 °C) than low (98 ... 115°C) or medium (120 ... 124°C) density PE.

Created algorithm for neutral system selection and checking by permissible touch voltage allows engineers easy and quickly select the optimal neutral point connection thus increasing reliability of network (reduce the number, duration and the risk of a double ground fault, as well as cable insulation does not degrade prematurely) and optimizing the costs of network construction. It is appropriate to choose isolated neutral in mixed medium voltage networks if the earth fault current is small, i.e., less than 30A for 6kV network, 25A for 10kV network, and 20A for 20kV network.

In case of higher fault current value is more appropriate to select compensated neutral, but if the bias voltage of line is more than 15% of the phase voltage then the resonant network should use with additional resistor or transposition.

In Latvia until 2011 earthing system was designed and created according to LEK 048 with standardized exhaust resistance of earthing system. In 2011 was accept new LVS EN50522. Unfortunately there was not a method for MV substation earthing system calculation in this new standard. Therefore in frame of promotion work has been taken participation in new LEK 136 "MV network neutral operation modes (isolated, compensated and low resistive neutral)" creation in order to establish the calculation method for medium-voltage substation earthing system. This method is designed for the touch voltage determining in MV networks in case of earth fault taking into account earth fault current return to the supply centre through medium-voltage cables metal screens, repeated earth electrodes in 0.4 kV network and also galvanically connected network earthing system of transformer substation.

In order to ensure that the network comply with the safety requirements of the selected neutral point connection it should be verified by touch voltage value, i.e., the potential increase on earthing system must be less than or equal to double touch voltage value. In case potential increase on earthing system is more than double touch voltage value it should taken measures that would limit potential increase on earthing system to a value equal to or less than twice the value of touch voltage.

Each country has a different geological structure and human resources costs therefore in Latvia can not be used research on CL construction costs carried out in other countries.

Therefore different types of medium voltage lines (OHL, COHL and CL) cost estimation algorithm developed in this doctoral thesis is desperately needed right now, implementing the DSO „Sadales tikls" 230 million investment program for approximately 6000km long OHL in forests replacment with 20 kV CL launched in 2011.

The developed algorithm makes it possible to quickly and easily perform comparative calculations in order to decide which of line construction type is the most advantageous from economical point of view- besides not only for construction cost point of view but also are assessed the operation and fault elimination costs.

The algorithm also takes into account what financial resources are used- internal or external- as well as circumstances of line installation- in forests, agricultural areas (including meadows, scrubs), or under rigid pavements.

In order to create general idea of cost comparison of CL, OHL and COHL was performed calculation example based on the cost data in Latvia. Calculation results shows that the CL construction and fault elimination costs are significantly higher than OHL and COHL but operating costs and is significantly lower than the OHL and COHL. Comparing cases when company is using external on internal financial resources shows that construction costs are significantly higher when company is using external funds.

Results of calculation show that from an economic point of view, CL is most disadvantageous solution in cities with rigid pavements but OHL- the most advantageous solution. However, for safety and the landscape reasons it is not recommended to use OHL in cities. Whole lifetime of new lines in rural areas without rigid pavements assuming that half of it is located in the forests and half in the agricultural land (including meadows, bushes) cost calculation results show that CL is most advantageous solution and COHL is most disadvantageous solution, if company for construction uses only internal financial resources but OHL is most advantageous solution and COHL is most disadvantageous solution if company for construction uses only external financial resources.

Whole lifetime of existing OHL lines replacement with CL or COHL in rural areas without rigid pavements assuming that half of it is located in the forests and half in the agricultural land (including meadows, bushes) cost calculation results show that CL and COHL is almost the same cost, if company for construction uses only internal financial resources but COHL is most advantageous solution if company for construction uses only external financial resources. Whole lifetime of existing OHL lines replacement with CL or COHL in cities with rigid pavements cost calculation results show that COHL is most advantageous solution than CL regardless of whether financial resources – internal or external- is used. However, it is important to note that the example was calculated using different assumptions which not always correspond to the real situation of a particular case. Therefore it should be used the algorithm described in doctoral thesis in order to assess each situation since it is possible to include all current data and conditions of lines construction thus obtaining a highly accurate calculation.

Also it should be noted that the calculation results of the example does not reflect the real costs of the 280km line. The calculation includes only those parameters that are different for each of the line construction types, since the aim of algorithm is to get comparative costs results of different construction line that would allow decide which one line construction type to choose. Furthermore the economic effectiveness must not be the only criterion of line construction type selection since it should be taken into account each line construction type utility in specific environmental conditions from a technical point of view in every situation because CL has not temporary interruptions and CL are independent on climatic conditions therefore with CL it is possible to achieve a significantly higher power supply reliability and quality of electric energy supply.

As technology continually evolving, there are changes in prices then such economic assessment with doctoral thesis proposed algorithm should be carried out for each situation separately using current prices since calculation example in doctoral thesis characterized only by a particular case (all assumptions used in the calculations described in 3.3. subchapter).

Elaborated method for touch voltage calculation in MV networks in case of earth fault taking into account earth fault current return to the supply centre through medium-voltage cables metal screens, repeated earth electrodes in 0.4 kV network and also galvanically connected network earthing system of transformer substation is very useful for distribution network exploitation engineers because in Latvia until 2011 earthing system was designed and created according to LEK 048 with standardized exhaust resistance of earthing system but in 2011 accepted new LVS EN50522 where earthing system basic parameter is permissible touch voltage instead of earthing system exhaust resistance, there is not a method for MV substation earthing system calculation.

Determined repeated earth electrode impedance effect on touch voltage value shows that by increasing repeated earth electrode impedance also increases touch voltage and vice versa. However, this correlation is proportional and not linear. Touch voltage value changes is more rapidly at lower repeated earth electrode impedance value changes. The obtained touch voltage values percentage change curve depending on the repeated earth electrodes impedance (30 Ω assuming as the basis) can be useful for distribution network exploitation engineers when evaluating usefulness of impedance changes in repeated earth electrode.

PEN limpedance effect on earthing system impedance and touch voltage is negligible- just 3.5%. Therefore it can be ignored in calculations.

Neutral point connection research is possible to continue by analysis of continuous partial discharges (PD) diagnosis and prevention opportunities for resonant network. The study of this question is extensive and therefore due to limited time for elaboration of doctoral thesis, research of this question is postponed to research in the future. Algorithm for selecting optimal line construction type based on economic considerations is possible to develop and complement by creating software that will make a convenient comparative calculation for practical use.

This doctoral thesis is the basis for my future scientific research.

„Science is not and will never be a finished book. Each meaningful achievement creates new questions. By the time each development comes to new and bigger difficulties.”

(Albert Einstein)

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