Estimation of Asset Insulation Condition by the Monte Carlo Method

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***Abstract* - The objective of the paper is to estimate the cable termination insulation level and developing of failure in it taking into account specific network grounding methods in Latvia. By means of PD measurement it is possible to estimate potentially dangerous terminations without power supply cut off. Termination failure probability during its lifetime is calculated by Monte Carlo method.**

***Keywords* - PARTIAL discharge, reliability, prognosis, insulation.**

I. Introduction

Largest power supply company in Latvia AS "Sadales tikls" is on pursue of increased power supply reliability to its customers. Potential failures are discovered by using different electrical equipment insulation condition assessment methods.

Discovery of potential failure rapidly decreases the cost of maintenance and save power supply company financial means by reducing the non delivered energy fines to the customer.

Disturbances of an electrical supply usually are caused by unpredicted failures of electrical equipment. Main reasons for failures are too fast degradation of insulation, network grounding method, installation and used material quality. All mentioned causes are bonded and can't be observed independently outside of this context. Pinpointing of potential failure is onerous by the fact that power supply lines are built or rebuilt as cable line in recent years and there are very least options for maintenance personnel to make a visual inspection and assess the condition of the insulation since cable lines are buried underground.

Power supply companies already have different methods to pinpoint the potential failure location but all of it requires power supply disconnection and relatively long time to do the assessment of the switchgear or cable line end termination insulation.

Most of the time predecessor of electrical equipment breakdown is the appearance of partial discharges (PD) within the insulation material during normal operation and since 2011. power supply company of Latvia AS „Sadales tīkls" has started to assess the level of insulation by PD measurements.

II. Physical Nature of Partial Discharge and it's Application

Accordingly to standard LVS EN 60270 [1] which is adopted in Latvia by the front page method partial discharge (PD) is a localized dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress, which does not bridge the space between two conductors, see Fig. 1. Usually cause of the localized PD is impurity inside the insulation material and overvoltage (surges) in the system. Insulation materials shall be homogenous without any contaminations like dust, air bubbles and other foreign bodies inside of it. Impurities that cause irregular voltages across the insulation material penetrate inside during manufacturing or installation process.

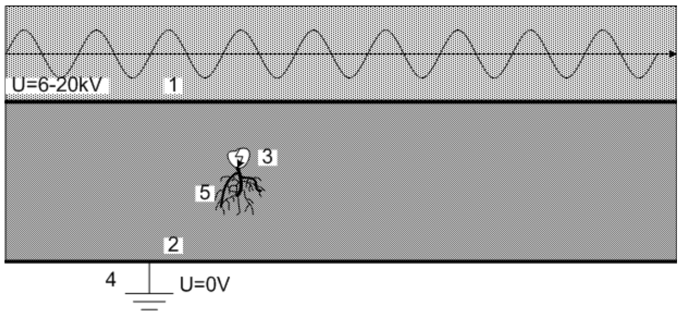

Fig. 1. PD within insulation adjacent to conductor. 1 – conductor, 2 – insulation, 3 – voids, 4 – ground potential surrounding, 5 – electrical tree.

During PD several undesirable physical processes occur: electrochemical reactions, emission of electromagnetic waves, acoustic disturbances and light/heat emission. These side effects cause structural changes inside the insulation and grew electrical trees which by time become conductive channels and bridge the insulation causing short circuit.

Purpose of the insulation is to separate different potential conductor from surrounding space which is grounded and not meant to conduct the operating current e.g. cabinet of the electrical equipment. Forces that affect the possible impurities (voids, dust etc.) inside of the insulation material depend on the difference of the potentials (voltages) to separate.

Manufactures of electrical equipment shall follow the rules of international standardization organizations (IEC, CENELEC) during the manufacturing process and make the products that comply with the set (predefined) properties. Electrical equipment is routine tested before it is shipped to the customer. One of routine tests for electrical equipment is a PD test. During this test voltage across the electrical equipment is gradually raised up to 2 times over nominal voltage and measured PD level shall be within set values.

Maintenance personnel use different tools to estimate the condition of the electrical assets including insulation level measurements and their ability to operate properly. Up to this moment insulation level measurements required asset disconnection from mains which was quite dispatcher time consuming to plan all the power supply shifts especially in radially fed parts of the network.

Acoustic PD measurements that are used to estimate the condition of the insulation level are done on-line without cutting off the power supply and taking off switchgear metal safety covers.

III. Overvoltage in the Distribution Network of Latvia

Power supply reliability and electrical safety depend on the type of feeding transformer 110/6-20kV medium voltage winding neutral grounding method. There are 134 feeding substations with 357 6-20kV busbar sections.

Historically medium voltage distribution network was developed as isolated neutral system. One of the benefits of this type of grounding is that it is possible to operate the network during sustained 1 phase ground fault. It shall be kept in mind that during ground faults voltage in undamaged phases increase up to line voltage as well as insulation is unfavorably heated due to increased currents.

Accordingly to [2] ground fault localization and fixing shall be started immediately after the tripping of the relay and ground fault protection system.

A. Distribution network grounding methods

Type of the network neutral grounding method is selected based on the 1 phase ground fault ampacity caused by capacitance that is created by the electrical lines.

In mixed (cable and overhead) 20kV network with ground fault up to I_c=20A isolated neutral system is preferred which doesn't have a physical connection to the ground, see Fig. 2.

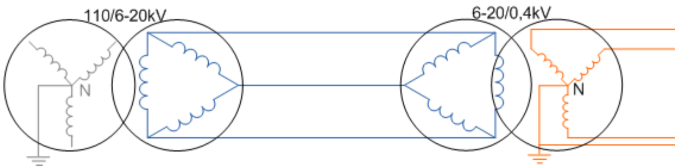

Fig. 2. Isolated neutral network.

Limit for the permissible ground fault in isolated neutral networks is selected so that it doesn't exceed the permitted continuous touch voltage for human being and livestock.

Highest grounding resistance within the network is 10Ω which might be at the medium voltage overhead line disconnection switches. This value of resistance is selected based on the presumption that highest permissible ground fault current is 25A in isolated neutral network. It limits dangerous over currents and overvoltage as well.

In case when 20kV network ground fault exceeds I_c>20A ground fault compensation system is introduced, see Fig. 3. to limit the ground fault current below acceptable 20A. This type of neutral grounding through the neutral grounding transformer is called a compensated neutral system. In an isolated and compensated network it is allowed to operate the network up to 8 hours during sustained 1 phase ground fault. During this time measures shall be taken to localize and recover the normal operation of the network.

Customer power supply in Latvia's largest cities (Daugavpils, Jelgava, Liepāja, Rīga, Valmiera) is mostly done by the cable line 6-10kV network. 1 km cable line capacity is up to 50 times (depending on the voltage level and conductor cross section) greater than the overhead line capacity hence creating high ground fault currents with very high threat for electrical safety. Ground faults in cable network are permanent and don't clear themselves as they do in 80% cases in overhead lines.

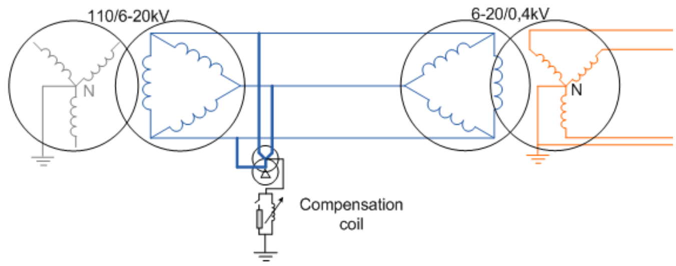

Fig. 3. Compensated neutral network.

Normally network with explicit cable lines is grounded through the low ohmic resistance creating low ohmic grounded neutral system to prevent large ground fault impact on the electrical equipment reliability and electrical safety, see Fig. 4. Low ohmic grounded system limits the fault current up to 1000A or even less and allows reliable and selective protection tripping at the beginning of the fault.

Introduction of ground fault compensation system within the cable line network didn't convinced the operational staff to be the most cost and technical effective system due to character of ground faults to become permanent faults. Sustained ground faults in the cable line network cause two phase ground faults or double ground faults in the other parts of the network escalating large scale interruptions and power supply disturbances.

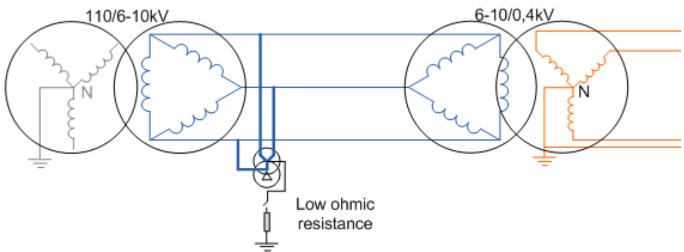

Fig. 4. Low ohmic neutral grounded network.

Spread of the network grounding methods for all 357 feeding substation bus bar sections at the 1st of January 2012 is shown in the table I. From the table it can be concluded that 20kV network is dominant by the covered territory even though the spread of customers is even at both voltage levels 6-10kV and 20kV since population density in cities is much higher and 6-10kV voltage level is mainly used for city power supply.

TABLE I

AMOUNT OF BUSBARS AND ITS GROUNDING METHOD

Busbar amount, n	Voltage level, kV	Neutral grounding method
124	20	isolated
72	20	compensated
42	10	isolated
19	10	compensated
59	10	low ohmic
41	6	isolated

B. Causes of surges

Medium voltage network elements which are dispersed or concentrated along the network make an oscillation circuits with their capacitances and inductances.

Oscillations don’t appear during normal network operation due to damping effect of the load resistance. Oscillations appear only during element tripping since it changes overall capacitance and inductance ratio. Connection and disconnection of network elements cause transient voltages which often turn in to surge. Amplitude of the inside network surges without surge limiting protection might exceed multiple times the phase voltage.

Main elements and events that facilitate the surges during connection or disconnection are:

- Line disconnection during its idling;
- Capacitor bank disconnection;
- Long line energizing or automatic reclosing;
- Transformer disconnection during its idling;
- 1 phase ground faults in isolated and compensated neutral network.

C. Surge values in context of neutral grounding

Network operation with increased voltage affects the insulation level and reduces its lifetime. Surges and ground faults in the network increase phase voltage above nominal value. Taking into account surge protection system requirements overvoltage level is limited to the value of 2 times the nominal phase value. Above this level line is disconnected.

At the ground fault experiments in the network with isolated neutral it was discovered that overvoltage during transient process might be as high as 3.5 times the nominal phase voltage [2], which is dangerous value for insulation and sometimes leads to breakdown.

Same experiments in compensated network showed that overvoltage during ground fault transient process doesn’t exceed 2,2 times the nominal phase voltage [2].

Overvoltage value depend on the fault resistance during the ground fault either it is purely metallic or intermittent arc.

When transient process of the metallic ground fault has stabilized voltage in the phases increase up to line voltage, see Fig.5. that is increased by the value of $\sqrt{3}U_{phase}$.

IV. ANALYSIS OF THE INSULATION FAULTS IN LATVIAS DISTRIBUTION NETWORK

During first 4 month of the 2012. several accidents has happened in the distribution network with totally burned down switchgears due to insulation failures. Total estimated cost of the financial losses is around 100`000Ls not taking into account the cost of undelivered energy and downtime, see Fig. 6. Insulation failures in 95% are discovered in the switchgear cable line end terminations or adapters.

Considerable investments are planned to develop 20kV cable network in near future by installing new cable lines and rebuilding existing overhead lines into the cable lines especially in forest areas to reduce outage time and frequency. Due to rapid cable network development it is important to operate with modern tools to forecast possible insulation failures and minimize the risk of outage and total damage of assets.

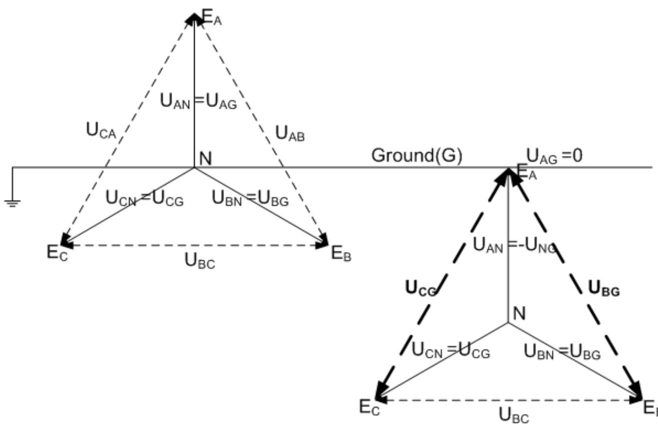

Fig. 5. Voltage phasor diagram during metallic ground fault (R=0).

Fig. 6. Leftover of the burned down switchgear.

Majority of insulation accidents occur due to lack of dielectric strength of the insulation. Evaluation of failures demonstrated that the cause of accidents is structural changes within the insulation material. Change of material structure is a gradual process due to PD occurrence inside the insulation material until its total breakdown with burn downs and large scale black outs.

Occurrence of PD inside of the insulation is triggered by uneven voltages across the insulation which is caused by:

- Voids and dirt inside of the insulation material due to unadjusted manufacturing quality monitoring process;
- Penetration of foreign bodies inside of the insulation material during installation process;
- Installation works that are done not accordingly to manufacturer recommendation;
- Cable line testing with increased voltage up to 3 times nominal voltage;
- Natural aging of the insulation material
- Weak maintenance of the assets.

V. Calculation of PD Occurrence Possibility

Insulation level monitoring method by PD measurements has been introduced in Latvia’s distribution network since fall of 2011. This insulation level assessment method doesn’t require complicated and time consuming asset disconnection to run regular insulation level tests. It should be noted that this method is not yet introduced in whole distribution network due to specific administrative separation and financial reasons.

To calculate the probability of failures in the assets Monte Carlo calculation method is used. Benefit of the method is that it takes into account known constants and independent variables and tells the probability to occur certain event with high confidence level. Failure probability calculation is done for the cable terminations.

Accordingly to inside the company regulation expected indoor switchgear lifetime is 40 years [4]. Monitoring of PD will be done 20 times every 2 years during asset lifetime. It is estimated that one termination (PD measurement) out of 60 terminations will be with damaged insulation and shall be fixed immediately.

Raw data for Monte Carlo calculation:

- 1 out of 60 terminations is dangerous and insulation degradation process is ongoing that might lead to failure;
- 20 consecutive measurements with interval of 2 years shall pass the PD measurement test;
- There is 50 % probability every PD measurement time that termination is potentially dangerous and will fail sooner than its estimated lifetime as expected;
- Probability shall be calculated with 99% confidence.

Calculation model is set up in the MS Excel software and due to its size is not shown here but main calculation steps shown further.

For the row of 20 measurements accidental value is selected each time out of 60 variations where one PD measurement outcome is not acceptable, see table II

TABLE II

RESULTS OF THE 20 MEASUREMENTS FOR 40 YEARS OF EXPECTED ASSET LIFETIME

Measure-ment No. 1	Measure-ment No. 2	Measure-ment No. 3	Measure-ment No. n	Measure-ment No. 20
valid	valid	valid	invalid	valid

Running 100 simulations there were summed 20 consecutive and valid measurements. Out of 100 simulations in 68 cases assets withstand 20 consecutive measurements without any failures and dangerously high PD which is the mean value.

After successful measurements it is necessary to calculate the standard deviation for 100 simulations. Z factor value is calculated which estimate [5], the distance range value with 99% confidence that the current measurement will be in distance range from mean value.

When Z factor is known it is possible to calculate, like (1), the maximum and minimum range level where constants (raw data) will be implemented with 99% confidence.

$$range_{upper,lower} = \frac{mean \pm st.dev \cdot zfactors}{\sqrt{\sum no.of.valid.outcomes}} \quad (1)$$

One more calculation is necessary to calculate the precision of average value that had to be found during the whole calculation, see the table III. 100 simulations give 12% precision of the result. To improve calculation precision is necessary to calculate how many simulations shall be run to achieve the desired precision, let’s say 2%, like (2).

$$n = \left(\frac{zfactors \cdot st.dev}{0{,}02} \right)^2 \quad (2)$$

Implementing (2) gives that it shall be 3583 simulation run to achieve desired precision with same raw data at the input. To find the final value same calculation algorithm is run after implementing 3583 simulations. Results for both simulations are gathered in the table III.

TABLE III

COMPARISON OF SIMULATION RESULTS

Calculated value	Simulation no 100	Simulation no 3583
Mean value	0,68	0,72
Standard deviation	0,469	0,45
z factors	2,576	2,576
Upper range	0,570	0,704
Lower range	0,809	0,743
Average value	0,69	0,724
Precision	0,119	0,019

Second and more accurate calculation gives that it is possible to say with 99% confidence that in 72-74% of PD measurement cases 1 out of 60 terminations in 20 consecutive measurements will be failed or even might cause large scale accident in the network.

VI. Summary

Specific network grounding and operation conditions of Latvia’s distribution network require relatively strict insulation level monitoring otherwise large scale black outs are possible on regular basis. PD monitoring in assets allow discovering and fixing terminations with degraded insulation in advance of the failure improving the overall reliability and electrical safety of the power supply.

Asset insulation monitoring will become more of the importance with roll out of the large scale rebuilding of the existing overhead line to cable lines besides the possible fine payments for undelivered energy and disturbances in the future. In the nearest 6 months real statistic PD measurements data will be collected and more accurate failure forecasting model developed as well as comparison of theoretical and real outcome.

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Mareks Zviedritis received B.sc, M.sc in electrical engineering at Riga Technical University, Riga, Latvia in 2004 and 2007 respectively.

He is presently an Electrical Engineer in research and standards department at AS "Sadales tikls" as well as Ph.D student in Riga Technical University. Work and research activities are held in Riga. In between B.sc and Ph.D. studies worked as Lighting Designer.

His research interests include reduction of outages caused by insulation degradation due to different middle voltage network grounding methods specifically ground fault impact on insulation.

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Mareks Zviedrītis. Izolācijas stāvokļa novērtējums ar Monte Karlo metodi

Pieaugot patērētāju prasībām pēc lielāka elektroapgādes drošuma reizē ar sadales tīklu novecošanos jāveic izolācijas stāvokļa monitorings, lai noteiktu iespējamās bojājuma vietas un veiktu preventīvus pasākumus tīkla izolācijas stāvokļa uzlabošanai. Pēdējo gadu pieredze rāda, ka Latvijas sadales sistēmā lielākās grūtības rada elektroietaises ar cieto izolāciju, piemēram, kabeļu gala apdares, izolatori un strāvmaiņi. Patstāvīgi pieaugot vidsprieguma kabeļu tīkla garumam palielinās arī izolācijas bojājumu risks. Elektroietaišu izolācijai savā kalpošanas laikā jāiztur vairākkārtīgi pārspriegumi, jo Latvijas tīkla daļās, kur ir izolēta vai kompensēta neitrāle atļauta vidsprieguma tīkla darbība pie vienfāzīga zemesslēguma, palielinot elektroapgādes drošumu. Palielināts spriegums zemesslēguma laikā veicina izolācijas paātrinātu novecošanos un samazina elektroietaišu kalpošanas laiku. Lai laicīgi atklātu iespējamās bojājuma vietas jāveic izolācijas stāvokļa monitorings, taču klasiskās izolācijas stāvokļa noteikšanas metodes veicamas pie atslēgta sprieguma, kas bieži nozīmē arī elektroapgādes pārtraukumu patērētājiem. Latvijas sadales tīklos ieviestai parciālo izlāžu mērīšanai ar akustisko metodi nav nepieciešama sprieguma atslēgšana, uzlabojot elektroapgādes drošumu un samazinot iespējamo bojājumu risku. Ņemot vērā statistiku par atklātajām potenciāli bīstamajām gala apdarēm, veicot akustiskos parciālo izlāžu mērījumus sastādīts matemātiskais modelis izolācijas stāvokļa un iespējamo bojājumu prognozēšanai ar Monte Karlo aprēķinu metodi. No aprēķiniem secināms, ka pastāv augsta bojājuma iespējamība kabeļu gala apdarēs un jāturpina periodisks izolācijas stāvokļa monitorings pie neatslēgta sprieguma.

Марекс Звиедритис. Оценка состояния изоляции методом Монте-Карло

Спрос потребителей к более высокой надежности электроснабжения в устаревших сетях распределения требует мониторинга состояния изоляции с целью определения возможных мест повреждений и проведения профилактических мероприятий для улучшения состояния изоляции сети. Опыт последних лет показывает, что в латвийской системе распределения большие трудности вызывает твердая изоляция (например, кабельные муфты, изоляторы и трансформаторы тока). Постоянный прирост длины кабельной сети среднего напряжения также увеличивает риск повреждения изоляции. Изоляция электрооборудования во время своей службы должна выдерживать многочисленные перенапряжения, поскольку в отдельных участках латвийской сети с изолированной или компенсированной нейтралью разрешена работа с однофазовым замыканием на землю, увеличивая надежность электроснабжения. Повышенное напряжение во время однофазового замыкания на землю ускоряет старение изоляции и сокращает срок службы электрооборудования. Для своевременного обнаружения возможных мест повреждений надо проводить контроль состояния изоляции. Классические методы контроля производятся при отключенном напряжении, что часто является причиной прекращения электроснабжения потребителей.

В латвийских распределительных сетях введены измерения частичных разрядов акустическим методом. Для их проведения не требуется отключение напряжения, что увеличивает надёжность электроснабжения и уменьшает риск возможных повреждений. Принимая во внимание статистику измерения акустических частичных разрядов и обнаруженных возможно опасных муфт, составлена математическая модель расчетов методом Монте-Карло для оценки состояния изоляции и возможных повреждений. Из результатов расчетов следует вывод, что существует большая возможность повреждений в кабельных муфтах и надо продолжать периодический контроль состояния изоляции при не отключенном напряжении.