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Single Phase Earth Fault Location in the Medium Voltage Distribution Networks

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Abstract-**This paper gives a description of the single phase earth fault location methods in the medium voltage networks. The single phase earth fault location in the medium voltage distribution networks is problematic now. The technical devices which are using in Latvia now do not allow to detect the single phase earth faults fast and high accuracy. Fast earth fault location should be possible by using the equipments which are calculating distance to earth faults. But precisely calculate the distance to the single phase earth faults in the medium voltage networks is very difficult. The paper presents the single earth fault location methods including the calculation methods for fault distance.**

I. INTRODUCTION

About 70 % of the faults in the medium voltage distribution networks are single phase earth faults. The consumer's networks not feel the single phase earth faults in isolated, compensated and high impedance grounded medium voltage networks. Therefore the system can operate some time during the single phase earth faults in medium voltage networks. But in low impedance grounded networks the fault current can reach till 1000 A during the single phase earth faults, therefore this regime is not allowed and damaged network should be switch off immediately. [1].

However a permanent single phase earth fault it is undesirable for the all types of neutral work regimes, because in the case of the intermittent arc could occur overvoltage. In the cable networks the single phase faults could develop to the double earth faults and short circuits. Switching off the several lines, increases undelivered electro energy quantity; damages cables thermally, decreases the lifetime of the electrical equipments, as well as the reliability of the power supply [1, 2]. In order to protect electrical equipments from the durable thermal effects, overvoltage and lifetime reduction; to increase reliability of the power supply, and to decrease undelivered electro energy quantity faults should be established fast and disconnected.

The distance protection (classical fundamental frequency method) is used to locate the single phase earth fault in the high voltage networks. The field experiments have shown that the distance protection is not possible to use at the medium voltage networks. In the medium voltage distribution networks the single phase earth faults can be located by using the highest harmonic devices, fault current indicators, or the equipments which is calculated the distance from the substation to the faulted place. The calculation the distance from the substation to the single earth fault in the medium voltage networks need a lot of parameters which are difficult to describe mathematically unlike to the high voltage networks. At the branched medium voltage distribution networks the precise calculation of the distance to the single phase earth fault is very difficult.

The paper review the some calculation methods for the distance from the substation to the single phase earth fault in medium voltage distribution networks and appraise the usability of the new fault location method for the Latvenergo distribution networks.

II. FAULT STATISTICS AND ECONOMIC ASPECTS

The Latvenergo internal normative documents state that the single phase earth fault location must be started immediately and the single phase earth fault may not exist in a network more than 8 hours.

Analysis of the cable faults at the Riga distribution network was carried out in the year 2002. From research results it is evident that the number of the faults per 100 kilometer increase every year. The number of the faults is increasing associated with the progressive aging of the cables. The faults in the network are damaging the cable insulation, leading to a decrease of the cable lifetime. As a result new faults can be caused by decreasing of lifetime.

According to the investigation results 42% of the total count of faults in 6 kV cable networks are the single phase earth faults, but have localized only 28% of single phase earth faults. In 10 kV cable networks 20% of the total count of faults are single phase earth faults, but have localized only 12% of single phase earth faults. It is also known that, on average 70% faults in medium voltage distribution networks are single phase earth faults. As a result, it can be concluded, that the single phase earth faults cross to double earth faults faster than single phase earth faults are founded and localized. Although the double earth fault length usually does not exceed 1.6 seconds (relay protection and power switches working time) but thermal influence to cables is very long due to the cables slowly to become cold (6 -7 hours) and it call for cable's insulation aging [1, 3].

If single phase earth fault does not switch off immediately, the decrease reliability of power supply caused the disconnection of users from electrical systems, the decrease lifetime of electrical equipment and increase of material losses.

III. SINGLE PHASE EARTH FAULT LOCATION METHODS

The localization of the single phase earth faults in medium voltage networks is difficult. In this paper we are presented the most popular single phase earth fault location methods, which are operated by using a current and voltage of the fundamental frequency, and by analyzing of the transient processes and the higher harmonics during the earth faults [4, 5]. The classification of the single phase earth fault location methods is shown in figure 1.

The single phase earth faults can be located by using the fault current indicators, higher harmonic devices, or by calculating the distance from the substation to the earth fault.

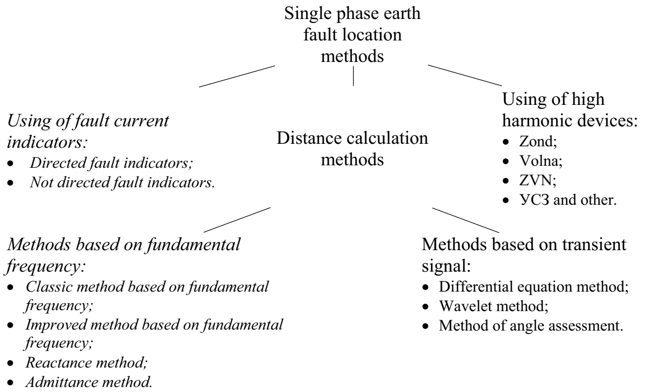

Fig. 1. Classification of single phase earth fault location methods

The single phase earth fault location can be faster and easier when the fault indicators and high harmonic devices methods are used. However, it is impossible to calculate a distance from substation to the earth fault by using these technical devices.

It is possible to increase the reliability of power supply, decrease the costs for the fault detection by calculating a distance to single phase earth fault. However to calculate the distance to single phase earth fault in medium voltage networks with high accuracy are very difficult. The distance calculating methods which are used in high voltage networks are not possible to use in medium voltage networks because they are very inaccurate.

The distance to the single phase earth fault can be calculated by using the fundamental frequency methods and transient methods. Although transient methods are not sufficiently precise, the fundamental frequency methods accuracy reaches around 10%.

IV. FAULT CURRENT INDICATORS

The fault current indicators are installed in medium voltage distribution network in order to detect the faulted section of power line when a fault occurs. The indicators have fixed the short circuit current or earth fault current in the section where indicators are installed (see Fig. 2).

The fault current indicators measure the electrical and magnetic fields around the electrical line wires for the fixing of faults.

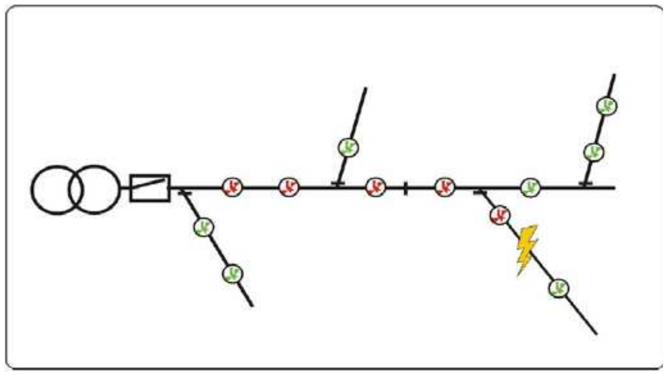

Fig. 2. Fault current indicators in a radial network: T – transformer, Q – switcher, k^1 – fault

CableTroll 3500 fault current indicators operation criteria during the short circuit [6]:

1. Line energized more than 5 seconds;
2. Zero sequence current exceeding a present value within 60 ms.

CableTroll 3500 fault current indicators operation criteria during the single phase earth fault:

1. Line energized more than 5 seconds;
2. Angular value between zero sequence voltage and zero sequence current is equal to exceeding value;
3. 50% increase in the zero sequence voltage.

By using of the fault current indicators the fault detection time is decrease two times. The time for the fault detection is possible to decrease more when fault indicators are switched on dispatching system.

However, the method has several shortages - unable to calculate the distance to the single phase earth fault; for the efficiency need to use much time more number of indicators; each indicator should be connected in to the dispatch system and networks must be in operation until fault will be found

A universal fault indicator was developed and patented in 2004 (by Dz. Baranovskis and J. Rozenkrons).

Operation of Universal fault indicator based on comparison the angle between zero sequence current and voltage with present value. Zero sequence current is measured using a zero sequence current transformer (ferranti) or a zero sequence sensors. Zero sequence voltage is measured by using current transformers in the 110 kV substation.

The criteria for the operation of the universal fault current indicators are the followings:

1. Zero sequence current exceeding a present value 10 mA;
2. Zero sequence voltage exceeding a present value 20 V;
3. Angular value between zero sequence voltage and zero sequence current is equal to exceeding vale.

For the indicator's connection in to the dispatch system was developed a data transmitting system which is much cheaper than equipments produced at the EU companies.

V. HIGH HARMONIC DEVICES

Density of the thigh harmonics in a network increase when occur the single phase earth fault. High harmonic devices measure magnetic field near the lines and it is possible to fix high harmonic. In a cable networks the high harmonic devices are connected to the ferranti transformers. In this way from the results of measurements it is possible to detect the damaged lines, or branches.

The method has several shortages: faulty line must be in operation until fault will found; earth fault location by using the high harmonic devices is time consuming, work consuming and economically disadvantageous process. If the faulted line is situated near to other lines or other electrical equipments it is not possible to detect a damaged line.

In practice to use the higher harmonics devices in place of single phase earth fault cannot be estimated because this devices operate inaccurately.

VI. CLASSIC METHOD BASED ON FUNDAMENTAL FREQUENCY

In general for the estimation of the distance to single phase earth fault need to calculate impedance of the network from the transformer to the earth fault. The estimated impedance value should be divided with a line specific reactance and then it is will be possible to get the distance from the transformer substation to the faulted place.

The classic fundamental frequency distance calculation method was developed for the high voltage networks and have used only here. In the medium voltage networks this method gives good results in the case of the low ohmic faults, but is not reliable in the case of the high ohmic faults [4].

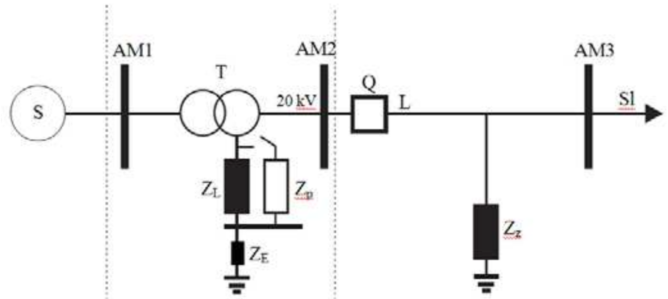

Fig. 3. Radial medium voltage network: S – system, T – transformer, ZL – Petersen coil impedance, Zp – additional impedance, ZE – grounding impedance, Zz – fault impedance, Sl – load, L – line, Q – switcher; AM1, AM2, AM3 – bus bar

The medium voltage radial network circuit is shown in Figure 3. The radial network simulation circuit in symmetrical components is shown in Figure 4. This circuit is usually have used for the value of single phase current calculation.

For the earth fault distance calculation in the compensated neutral networks it is possible to use in Figure 5 shown scheme. Often parallel a compensation coil is installed an additional resistor Zp to increase the active component of the fault current. The additional resistor and compensation coil have connected to the earth by using grounding Z_E. In normal operating regime the grounding impedance is practically does not affect the network parameters. During single phase earth fault the grounding impedance drown three times. It is neglected to use classical method network capacitances [4].

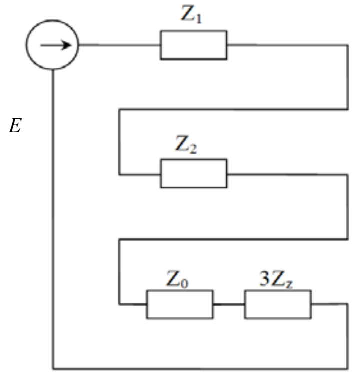

Fig. 4. Network simulations model in symmetrical components: E – voltage source, Z_1 – positive sequence impedance, Z_2 – negative sequence impedance, Z_0 – zero sequence impedance, Zz – fault impedance

For the calculation of the impedance from the substation to faulted place by using Figure 5 a simulation model have been developed [7].

$$\dot{Z}_{1L1} = \frac{\dot{U}_A - \dot{I}_z \cdot \dot{Z}_z - \dot{I}_{komp} \cdot \dot{Z}_E}{\dot{I}_A + \dot{I}_\Sigma \cdot k_0} \tag{1}$$

where $\dot{U}_A$ – faulty phase voltage;
$\dot{I}_z$ – fault current;
$\dot{Z}_z$ – fault impedance;
$\dot{I}_{komp}$ – current during compensation coil;
$\dot{Z}_E$ – grounding impedance;
$\dot{I}_A$ – faulty phase current;
$\dot{I}_\Sigma$ – residual current;
k_0 – coefficient.

Value of the coefficient k_0 can be estimated:

$$k_0 = \frac{1}{3}\left(\frac{Z_{0L}}{Z_{1L}} - 1\right), \tag{2}$$

where Z_{1L} – positive sequence line impedance related to one length unit;
Z_{0L} – zero sequence line impedance related to one length unit.

Residual current $\dot{I}_\Sigma$ is equal:

$$\dot{I}_\Sigma = \frac{1}{3\dot{I}_{0p}}, \tag{3}$$

where $\dot{I}_{0p}$ – zero sequence current at the measuring point.

Equation (1) is the basis for an algorithm in a single phase earth fault distance calculation. Using the classical fault distance calculation method the some parameters are neglected [4]:

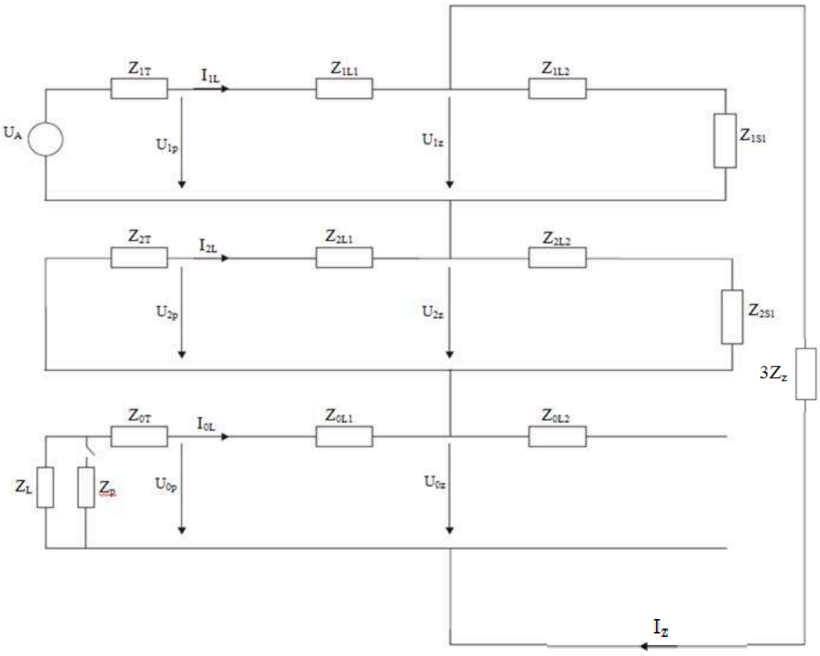

Fig. 5. Network simulations model: U_A – voltage source; I_{1p}, I_{2p}, I_{0p} – positive, negative and zero sequence current at the measuring point; I_{0T} – zero sequence current of the transformer; U_{1p}, U_{2p}, U_{0p} – positive, negative and zero sequence voltage at the measuring point; Z_{1T}, Z_{2T}, Z_{0T} – positive, negative and zero sequence transformer impedance; Z_{1L1}, Z_{2L1}, Z_{0L1} – positive, negative and zero sequence line impedance; Z_{1L2}, Z_{2L2}, Z_{0L2} – positive, negative and zero sequence line impedance; Z_{1Sl}, Z_{2Sl} – positive, negative and zero sequence load impedance; Z_L – arc suppressing coil impedance; Z_P – additional impedance

1. network capacitances are neglected because in the solid grounded neutral networks the earth fault current at the faulted place is similar to the measured current at the measuring point;
2. the classic method does not consider the fault impedance and earth fault current therefore the resistance at the faulted place is very small in the solid grounded neutral and low impedance grounded networks;
3. for the calculation the distance to the single phase earth fault have used only the reactive part of calculated impedance;
4. the grounding impedance and current which goes through compensation coil.

With the assumptions above, equation (1) can be simplified to equation (4):

$$\dot{Z}_{1L1} = \frac{\dot{U}_A}{\dot{I}_A + \dot{I}_\Sigma \cdot k_0}, \quad (4)$$

where $\dot{U}_A$ – faulty phase voltage;
$\dot{I}_A$ – faulty phase current;
$\dot{I}_\Sigma$ – residual current;
k_0 – coefficient.

As mentioned above, the calculation of the distance to the single phase earth fault have used only the reactive part of the calculated impedance [4]. Dividing the imaginary part of the impedance by the specific positive sequence line impedance we will get the fault distance:

$$l = \frac{1}{x_1}\operatorname{Im}\left(\frac{\dot{U}_A}{\dot{I}_A + \dot{I}_\Sigma \cdot k_0}\right), \quad (5)$$

where l – fault distance;
x_1 – specific positive sequence line impedance.

Equation (5) is used in the high voltage solid or low impedance grounded networks. In the medium voltage distribution networks a value of the fault impedance usually is large, therefore classical algorithm cannot be used for the distance calculation in the distribution networks.

VII. IMPROVED METHOD BASED ON FUNDAMENTAL FREQUENCY

Calculate the distance to the single phase earth fault in medium voltage network is more difficult than in the high voltage networks. To increase estimation of accuracy, fault current I_z, fault impedance Z_z, grounding impedance Z_E, and current during through compensation coil I_{komp} must be considered [4].

The fault impedance can be calculated by dividing the phase voltage $\dot{U}_A$ from the faulty phase at residual current $\dot{I}_\Sigma$. Calculation takes into account active component of impedance:

$$R_z = real\left(\frac{\dot{U}_A}{\dot{I}_\Sigma}\right) \quad (6)$$

As shown in Figure 6 the fault current I_z consist of the inductive current of the neutral point impedance and the capacitative currents of the faulty line and of the other feeders.

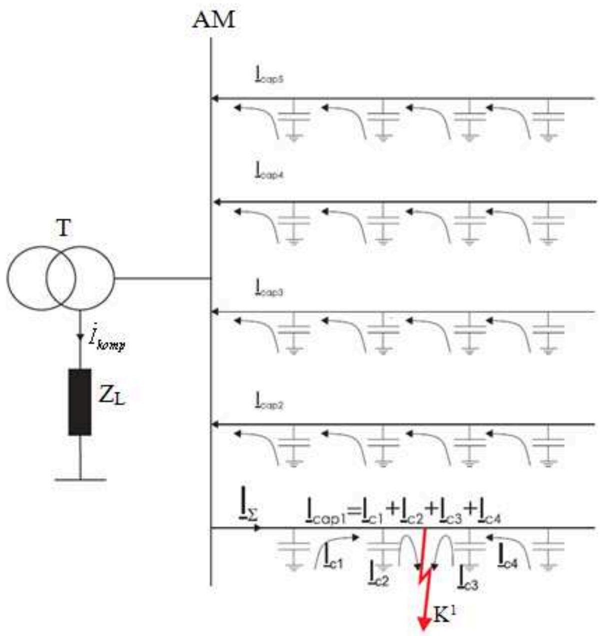

Fig. 6. Compensated network: T – transformer; Z_L – arc suppressing coil impedance; AM – bus bar; $I_{cap1} \div I_{cap5}$ – 1 ÷ 5 capacitive current from feeders; $I_{c1} \div I_{c4}$ – distributed line capacitive currents; $\dot{I}_{\Sigma}$ – residual current; $\dot{I}_{komp}$ – arc suppressing coil current; K^1 – single phase earth fault

From [4] derive that the fault current is proportional to the measured zero sequence voltage and the capacitive current from the faulty line. Then fault current at the earth fault point can be calculated as followed:

$$\dot{I}_z = \dot{I}_{\Sigma} + \dot{I}_{cap1} \cdot \left| \frac{\dot{U}_{0p}}{\dot{U}_{Anom}} \right| \quad (7)$$

where $\dot{I}_z$ – fault current;
$\dot{I}_{\Sigma}$ – residual current;
$\dot{I}_{cap1}$ – capacitive current from faulty line;
$\dot{U}_{0p}$ – measured zero sequence current;
$\dot{U}_{Anom}$ – nominal phase voltage.

Inserting equation (6) and (7) into equation (1) generate equation 8 which is used to calculate the network impedance.

$$\dot{Z}_{1L1} = \frac{\dot{U}_A - real\left(\frac{\dot{U}_A}{\dot{I}_{\Sigma}}\right) \cdot \left(\dot{I}_{\Sigma} + \dot{I}_{cap1} \cdot \left|\frac{\dot{U}_{0p}}{\dot{U}_{Anom}}\right|\right) - \dot{I}_{komp} \cdot \dot{Z}_E}{\dot{I}_A + \dot{I}_{\Sigma} \cdot k_0}, \quad (8)$$

where $\dot{U}_A$ – faulty phase voltage;
$\dot{I}_{\Sigma}$ – residual current;
$\dot{I}_{cap1}$ – capacitive current from faulty line;
$\dot{U}_{0p}$ – measured zero sequence current;
$\dot{U}_{Anom}$ – nominal phase voltage;
$\dot{I}_{komp}$ – arc suppressing coil current;
$\dot{Z}_E$ – grounding impedance;
$\dot{I}_A$ – faulty phase current;
k_0 – coefficient.

The fault distance is calculated by using the imaginary part of the calculated impedance $\dot{Z}_{1L1}$ [4]:

$$l = \frac{1}{x_1} \mathrm{Im}\left[\frac{\dot{U}_A - real\left(\frac{\dot{U}_A}{\dot{I}_{\Sigma}}\right) \cdot \left(\dot{I}_{\Sigma} + \dot{I}_{cap1} \cdot \left|\frac{\dot{U}_{0p}}{\dot{U}_{Anom}}\right|\right) - \dot{I}_{komp} \cdot \dot{Z}_E}{\dot{I}_A + \dot{I}_{\Sigma} \cdot k_0}\right], \quad (9)$$

where l – fault distance;
x_1 – specific positive sequence line impedance.

VIII. REACTANCE METHOD

The method is based on equation, which draft on II Kirchhoff rule for the faulted phase. Transforming the given equation has obtained expression for the calculation of the single phase earth fault distance [8].

However the methods authors didn't give all export for the all mathematic formulas and mathematical justification. The given method has not been tested in practice, and it is therefore difficult to draw conclusions about the accuracy. Carrying out the reactance method in 110 kV substation is measured zero sequence current and zero sequence voltage. Knowing the given parameters have calculated the distance to the earth fault.

IX. ADMITTANCE METHOD

One of effectiveness method for the calculating earth fault distance in the compensated medium voltage networks is the admittance method. The accuracy of this method is about 5%. But admittance method can be used only in resonant grounded loop networks (Figure 7).

Normally loop is open and is closed only in the case of earth fault. The loop is made by closing a breaker at the point of the network separation. The zero sequence currents are measured before and during single phase earth fault. The measured current differences ΔI_{0A}, ΔI_{0B} are proportional to the zero sequence admittance up to the fault [9]. Knowing the differences of the zero sequence current it is possible to carry out the network impedance from point A to the faulted place:

$$x_A = \frac{\Delta I_{0B}}{\Delta I_{0A} + \Delta I_{0B}}, \quad (10)$$

where ΔI_{0A} – zero sequence current difference in the line A;
ΔI_{0B} – zero sequence current difference in the line B.

Knowing the impedance of the faulted place the distance to the single phase earth fault is calculated.

The real electrical networks consists the cables and overhead lines; contains the branches and different cross sections of conductors. Take to account above mentioned the accuracy of the admittance method decreases. To improve the accuracy of the calculation the special programs have

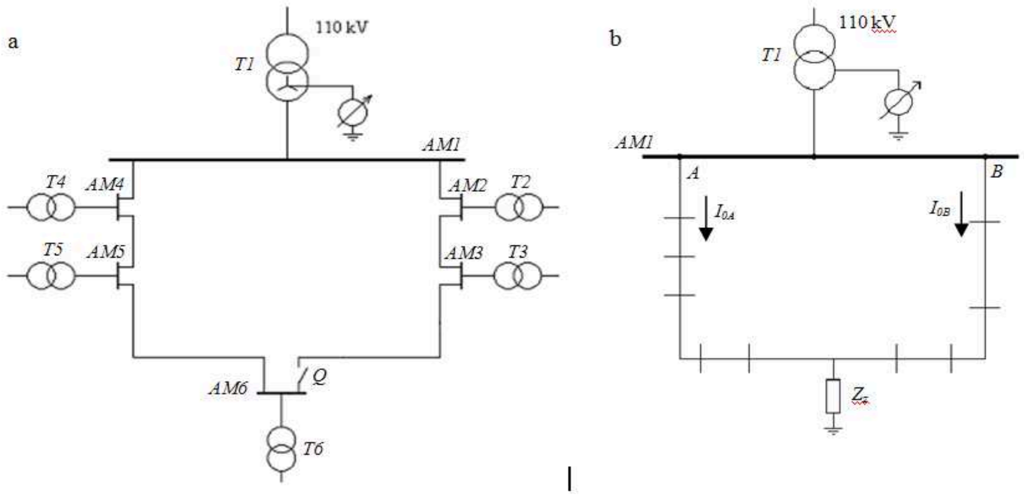

Fig. 7. Loop network: a – normal regime; b – single phase earth fault regime; *T1* ÷ *T6* – transformers, *AM1* ÷ *AM6* – bus bars, *Q* – switch, Z_z – arc suppressing coil impedance, I_{0A} – zero sequence current through point *A*, I_{0B} – zero sequence current through point *B*

developed. These programs are implemented in standard computer.

The admittance methods have been tested in German Energy System MEAG. Experimental results shown, that admittance method works successfully [9].

X. METHODS BASED ON TRANSIENT SIGNALS

The method is based on transient during the single phase earth fault. It was proved that the inductance of the fault place is proportional to the fault distance.

The network inductance can be calculated by solving the differential equation that describes the fault circuit. To calculate the network inductance, the wavelet transformation can be used. The fault distance [4] is then obtained by dividing the network inductance of the fault place by inductance per kilometer.

The method based on transient signals is developed in Helsinki University of Technology. Authors did not give enough details on its accuracy and usability. Also the method has not a sufficient mathematical basis and it has not been tested in practice.

XI. CONCLUSION

Publication includes research of the singe phase earth fault detection devices at the Latvenergo distribution networks and the investigation of the data analysis about the faults in Riga Electrical Networks.

In the paper there were systematized single phase earth fault location methods. There are described operation of the fault current indicators and high harmonic devices. Using the fault current indicators can be detected only faulty line stage or faulty branch. Using high harmonic devices single phase earth fault location is very time-consuming process.

By calculating distance from the 110/20 kV substation to the single phase earth fault it is possible to locate fault very fast and accurately. In the paper there are shown most promissory fault distance calculation methods.

Calculating algorithms which are used in high voltage networks in medium voltage distribution networks are very inaccurate. The usability of the fault location methods depends on the network neutral regime.

In the compensated or resistance grounded networks improved method based on fundamental frequency provide very satisfying results. This method can be used in the cable networks as well as in the overhead lines. The maximum aberration is in a range of 10 %.

Operating experiments shows that in medium voltage loop networks admittance method gives mean accuracy of 5 %. By further development of the method, the accuracy can be increased. Admittance method has been used in actual MEAG electrical networks.

As shown methods based on transient signals can not be used in actual networks.

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