Neutral Point Treatment and Earth Fault Suppression

Osmo Siirto, Mika Loukkalahti, Markku Hyvärinen, Pirjo Heine, and Matti Lehtonen

***Abstract*--Earth fault management in medium voltage networks involves assessing of customer interruptions, challenges in fault clearing processes and safety issues. The major advantage by allowing sustained earth faults is the avoidance of customer interruptions. However, the network operation with sustained earth faults does not only include welfare. The paper will generally discuss the advantages and disadvantages of operating the network with sustained earth faults. In addition, in the paper, the Helsinki medium voltage network and the developments in neutral point treatment and network operation during earth faults will be outlined. The paper presents the earth fault analysis in the Helsinki 10 kV network and compares the results to a reference analysis. Based on the analysis, the paper presents the possibilities and limitations of a sustained operation with earth faults. The paper also presents the strategy steps of managing sustained earth faults as well in the 10 kV and 20 kV areas and the required long term development steps.**

***Index Terms*--Compensation, cross country fault, earth fault, interruption, power quality, protection, reliability, smart grid.**

I. Introduction

WHEN considering single phase earth faults in medium voltage (MV) networks handling safety issues, especially touch voltages, is the most important aspect. In addition, the earth fault management includes balancing between customer interruptions and challenges in fault clearing processes. By allowing sustained earth faults the major advantage is avoiding customer interruptions. Especially in city areas, this is highly appreciated.

However, the network operation with sustained earth faults also has some drawbacks. The major disadvantage is the increased risk of cross country faults. A sustained earth fault evolving to a cross country fault results in two simultaneous faults at various locations. This means a considerably wider area of customer interruptions and a more laborious fault clearing and repairing process.

In this paper, the operation of Helsinki MV networks in earth faults is presented. Helsinki has announced as its goal to halve the SAIDI (System Average Interruption Duration Index) down to six minutes by 2015. The main means to achieve this goal is to allow the network operation with sustained earth faults. Therefore, changeover from an unearthed to a compensated neutral point treatment of the 20 kV network is needed. The development steps to achieve this are discussed.

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II. Earth Faults and Safety

A. Earth Faults

A single phase earth fault is caused by an earth connection of one of the phases (Fig. 1). The voltage of the faulted phase collapses while the voltage on the other two phases rises. The voltage of the sound phases can reach the phase-to-phase voltage [1]–[3] (Fig. 2). This voltage raise exists on the whole supply area of the main transformer.

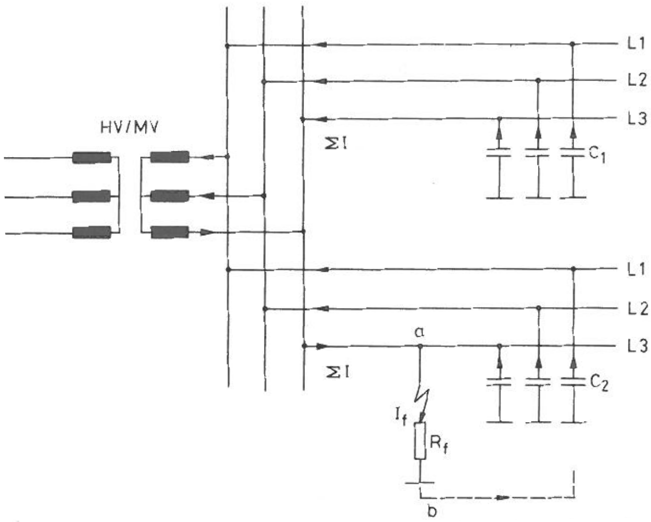

Fig 1. A single phase earth fault on an isolated system [2].

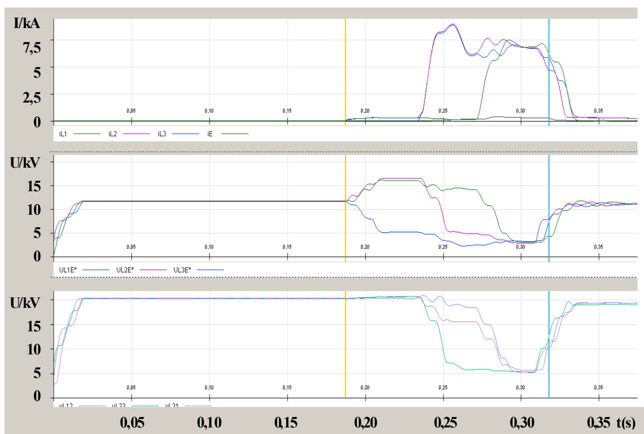

Fig. 2. Phase currents, phase-to-ground voltages and phase-to-phase voltages in a single phase earth fault turning first into a two phase short circuit and then a three phase short circuit, Helsinki 20 kV station.

In an unearthed system, if fault resistance is zero, the single phase earth fault current can be calculated as follows,

$$I_e = 3\omega C_e E \quad (1)$$

where I_e is the earth fault current (A), $\omega = 2\pi f$ is the angular frequency (1/s), C_e is the phase capasitance of the network (F) and E is the phase voltage (V) [3].

The voltage level of the MV network and the types and lengths of the feeders in a particular galvanically connected network determine the earth fault current.

To manage and limit the earth fault currents, the operating areas of MV networks must be restricted geographically. Furthermore, the networks can be compensated. Typically, in a compensated system, a reactor is connected to the star point of the primary transformer. The inductive reactance of the reactor is set near the value of the capacitive reactance of the whole cable network (resonant earthing). In an earth fault, the capacitive and inductive currents are opposite thus resulting in a small earth fault current [4]. This creates challenges in fault detection and localization and therefore also a temporary (low) resistance neutral earthing is additionally applied (Fig. 3). In the occurrence of an earth fault, this resistor is switched on to increase the neutral current and it thereby enables the protection to detect the faulted feeder and to alarm [5].

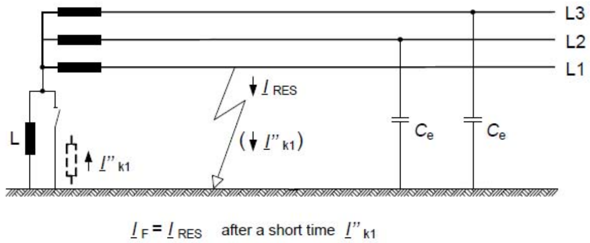

Fig. 3. An earth fault current in a system with resonant earthing and temporary low resistance neutral earthing. [4].

When a single phase earth fault occurs, the protection traditionally trips the faulted feeder from the network and an interruption is experienced. In this paper, it will be presented and discussed a case of a network operation with sustained earth faults. In this approach, earth fault currents and voltages are kept sufficiently low and when a single phase earth fault occurs only an alarm is sent to the operator and the operation of the network will be continued during the fault clearing process.

B. Earth Faults Developing into Cross Country Faults or Short Circuits

During an earth fault and the voltage raise of the sound phases another earth fault can occur between a sound phase and the earth. The location of the second earth fault can be different from the original one. These so called cross country faults result in a considerably wider fault area of customer interruptions and more laborious fault location, isolation and repairing processes. Also the fault currents are higher and they flow through the ground causing hazard.

Earth faults may also progress into multipole faults in the original fault location. Fig. 2 presents an example of an earth fault turning first into to a two phase short circuit and then to a three phase short circuit.

C. Safety Criteria

When considering electricity and safety of human beings, the danger is that a current will flow through the region of the heart possibly causing ventricular fibrillation. For safety purposes, it is required to determine limit values. Because the body current is difficult to measure the body current limit is translated into voltage limits for comparison with the calculated step and touch voltages. As a general rule, meeting the touch voltage requirements satisfies the step voltage requirements because the tolerable step voltage limits are much higher than touch voltage limits due to the different current path through the body [5].

In addition, the higher the voltage, the shorter time it may affect to a human being without causing danger. Fig. 4 shows the dependency between the permissible touch voltage and the duration.

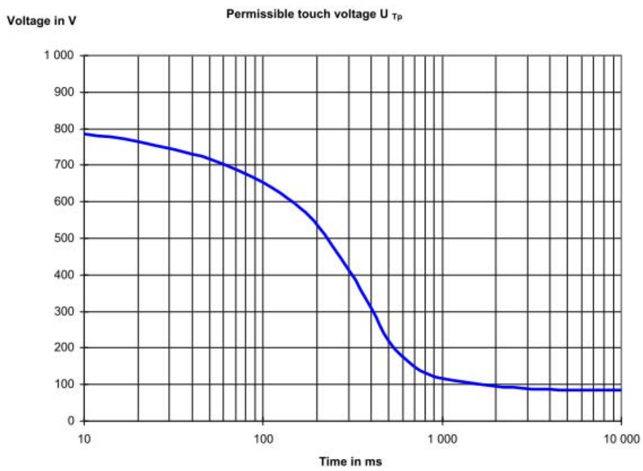

Fig. 4. The permissible touch voltage. [5].

In Fig. 4, the permissible touch voltage in a sustained operation is the voltage at the very right end of the curve. According to the standard EN 50522, a value of 80 V may be used as a permissible touch voltage [5]. The permissible touch voltage values are considered to be satisfied if either one of the conditions is satisfied:

- The relevant installation is a part of a global earthing system.
- The earth potential rise does not exceed the double value of a permissible touch voltage.

So the planning criteria are that the earth potential rise in a sustained earth fault must not exceed 160 V. EN 50522 standard says that every earth fault will be disconnected automatically or by hand. Thus, touch voltages of very long or indefinite duration do not appear as a consequence of earth faults [5]. In the Finnish standard SFS 6001, High-voltage electrical installations, there is a national condition, that the earth fault shall be disconnected within two hours [6].

III. Study Case Helsinki

A. MV Network in Helsinki

The MV network in Helsinki is built with underground cables. The network consists of two voltage areas. The city urban core areas have 10 kV networks with isolated neutrals and these networks are operated under sustained earth faults.

The protection in the 10 kV network can be alarming because of the low earth resistance, lower voltage level, and shorter cable lengths fed by the power transformers. Thus, the earth fault currents and touch voltages are small and the safety criteria are fulfilled.

The suburban 20 kV areas have had MV networks with isolated neutrals, except for one new substation with a compensated neutral. The earth fault current of the 20 kV network is on average four times greater than the earth fault currents in the 10 kV network. Thus, to fulfill the safety criteria the protection in the 20 kV network is tripping and the sustained operation would not be possible. In the 20 kV network, the earth fault protection trips the faulty line thus leading into customer interruptions.

B. Reducing SAIDI Values by Compensating the 20 KV Network

As a long term development goal, following the priciple of continuous improvement, Helen Electricity Network Ltd. has announced a target of halving SAIDI from its long term average value of ca. 12 minutes down to 6 minutes during the coming years. To reach this aim, it has been decided to develop the network so that also the 20 kV network can be operated with sustained earth faults. In this process, it is needed to change the neutral treatment of the 20 kV network by installing compensation coils to the neutral points.

The compensation brings many advantages. Small earth faults currents mean small touch voltages. When the safety criteria are satisfied the network can be operated with sustained earth faults. Customer interruptions can be avoided. Especially in city areas with high load density, this is highly appreciated.

By reducing the earth fault current, also the stress for the network devices is decreased. The power frequency voltage stress is the same, but the earth fault current and transients stresses are mitigated. E.g. in Helsinki, there has been ten voltage transformer failures during the past 20 years causing substation level interruptions. The compensated neutral decreases the stress to substation devices and thus decreases the number of substation faults with high customer outage costs.

The reduced earth fault current also increases the possibilities for self extinction of the arc, thus mitigating the damage caused by the fault. The compensated neutral also decreases the possibilities for the earth fault to develop into a short circuit fault.

On the opposite, also disadvantages are arisen. The most considerable drawback of the compensated neutral and sustained earth faults is the increased probability of earth faults to evolve into cross country faults. The statistics in Helsinki shows that the interruptions caused by cross country faults lasts in average about twice as long as other interruptions.

The major reason for cross country faults is the increased phase voltage on the non faulted phases. The phase voltage rises up to the level of the phase-to-phase voltage. This voltage rise stresses the insulation of the network and the risk for the already weak network points to break down is evident.

In a network with a compensated neutral, the protection is set to measure the active current instead of measuring the reactive current as in a case of an isolated neutral. This means that if the earth fault current compensation is turned off and the network is used with isolated neutrals the relay settings must be changed.

C. Fault Analysis Case

SAIDI is an important index in evaluating the success of the network management. In Helsinki, the main means for lowering the SAIDI values is to change the operation in the 20 kV network from tripping of earth faults to sustained earth faults and alarming. This is achieved by changing the neutral treatment of the 20 kV network to have compensated neutrals. The effect of this development step on the SAIDI values has been evaluated for the investment plans and decisions and is reported in the following.

Analysis is based on the statistics of earth faults on the Helsinki 10 kV network with a sustained operation from years 2004 to 2010. There have been altogether 68 earth faults meaning an average of ca. ten earth faults per one year. From the fault statistics it can be seen that 76 % of the earth faults are single earth faults and 24 % are two or three phase earth faults. The average SAIDI in years 2002–2010 in the Helsinki 10 kV network with a sustained earth fault operation was ca. 6 minutes and in the Helsinki 20 kV network about 13 minutes. Assuming that after compensating the 20 kV network all the single phase earth faults are no more causing interruptions, SAIDI could reduce down to 3 minutes (Fig. 5). However, the results from the earth fault analysis in the Helsinki 10 kV network shows that 24 % of the earth faults are evolving into cross country faults. This means an average SAIDI of 6 minutes in the 20 kV network instead on the previous estimation of SAIDI of 3 minutes (Fig. 5). Further, the statistics in Helsinki shows that the interruptions caused by cross country faults lasts in average about twice as long as other interruptions. When taking also this into the estimation, it would lead to a SAIDI value of 8 minutes (Fig. 5).

On the other hand, a considerable proportion of the SAIDI is caused by large substation outages. Moving from an isolated neutral to a compensated neutral will decrease the earth fault current stress to substation devices, especially to voltage transformers. After the interruption of a single phase fault, a charge will remain in earth capacitances of cables. This charge will be removed by a DC transient flowing in an unearthed system through the voltage transformers, often causing excessive burden. In a compensated system, the coil offers better conducting path for this DC transient. This will decrease substantially the amount of substation outages. Also the difference in the multipole earth fault ratio between a sustained or tripped operation is in reality less than the statistical 24 %, since some faults progress into multipole failures in the course of the operation time of the protection relay, see example in Fig. 2. A rough estimation is that these two factors combined will compensate the SAIDI increase caused by the potentially longer interruptions of cross country faults.

Taking into account all the previous factors results to an average SAIDI of ca. 6 minutes in the 20 kV network (Fig. 5). This is in line with the fault statistics in the Helsinki 10 kV network with the sustained earth fault operation. The average SAIDI in years 2002–2010 in the Helsinki 10 kV network with the sustained earth fault operation was ca. 6 minutes.

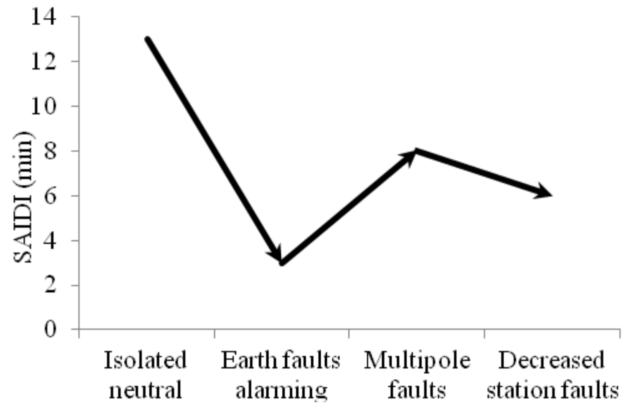

Fig. 5. Estimating the effect of a compensated neutral to SAIDI.

D. Comparison of Earth Faults in Helsinki and Dresden (Germany), Experiences of Neutral Point Compensation in Central Europe and Italy

To seek support to the development steps of Helsinki, Helsinki data is compared with the data from Dresden, Germany [7]. In Helsinki, 24 % of the faults turn into multi-pole failures, in Dresden the ratio is 35 %, Fig. 6.

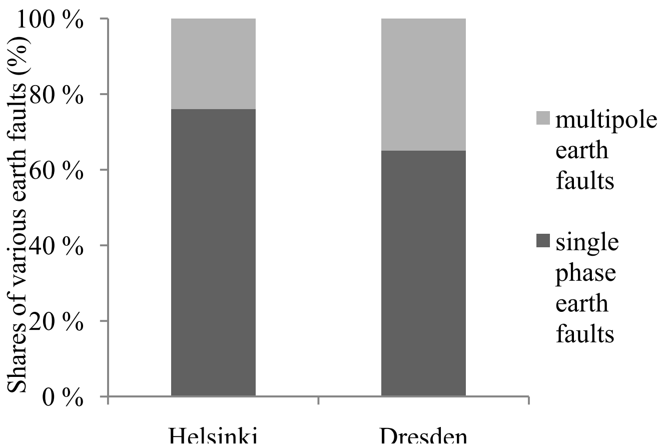

Fig. 6. Shares of different earth fault types, Helsinki, Dresden.

There can be several reasons for the differences in shares, for example:

- different voltage level;
- different cable/joint/termination types;
- different age and condition of the network.

This comparison between Helsinki and Dresden shows that the share of earth faults evolving into multipole earth faults can be higher than the Helsinki 10 kV value of 24 % presented in the previous SAIDI estimation. The higher ratio of earth faults evolving into multipole earth faults decreases the benefit of compensating the neutral.

However the high number of multipole failures is not only a negative issue. The voltage stress caused by an earth fault tests the insulation of the network and finds the weak spots. Usually after a high intensive earth fault period, less faults are experienced during the coming years on the feeder area of the power transformer since the weak points have already been replaced. This is shown in the Fig. 7 which shows the frequency the MV cable/joints/terminal faults in Helsinki 10 kV network during the years 2004–2011.

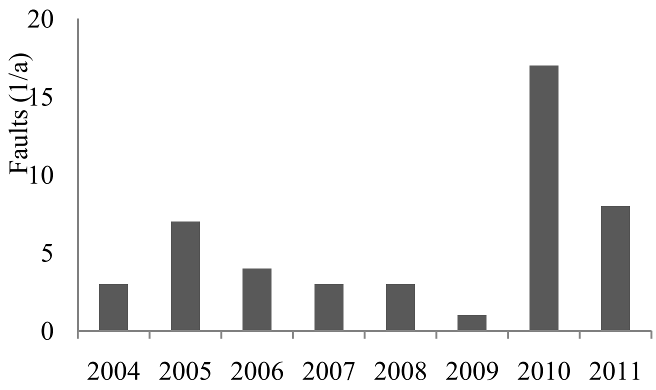

Fig. 7. MV cable/joints/terminal faults in the Helsinki 10 kV network during 2004-2011.

To better manage the condition of MV cables, the utility can by using cable condition monitoring discover the weak points in networks before they evolve into earth faults. So the cable condition monitoring supports and increases the benefit of compensating the neutral.

In Central Europe a majority of the medium voltage and high voltage transmission systems are operated as resonant grounded grids. The motivation to keep on operating the electrical power networks with resonant grounded neutrals is derived from the good experiences with the high continuity of supply. This is due to the self extinguishing properties of phase-to-earth arcs in such grids, especially in grids with a large proportion of overhead lines. Because of the out-standing feature of continuous operation during earth faults, the resonant grounded grids can be classified as self healing grids [8].

Also in Italy in ENEL MV networks, the net reduction in the number of interruptions due to Petersen coil is significant. The reduction in the number of interruptions due to the introduction of the new grounding system is as follows: 51 % reduction intransients, 38 % reduction in short interruptions and 26 % reduction in long interruptions [9].

E. Effect of Compensated Neutral to Distribution Automation

Compensating has been evaluated as a strong instrument to halve the SAIDI values (through reducing SAIFI System Average Interruption Frequency Index). In addition, distribution automation has been adopted as another means to lower SAIDI values (through reducing CAIDI Customer Average Interruption Duration Index).

When considering multipole faults and distribution automation, also the number of multipole earth faults can be decreased if the fault location, isolation and recovery processes can be accelerated. This means a requirement of fast automatic fault management functions in distribution automation.

In Helsinki during the years 2004–2010, about 60 % of the multipole earth faults arose within two minutes from the first earth fault, Fig. 8. The average time was ca. 30 minutes, however the median was one and a half minute. Only three out of sixteen multipole earth faults began after one hour. So the probability of multipole earth faults decreases rapidly after the first minutes of a sustained earth fault. Fig. 8 presents durations of only those earth faults that have evolved into multipole faults in the 10 kV network. With distribution automation the possibility an earth fault to evolve to a multiple fault can be decreased. These multipole faults result typically in a considerably wider fault area and thus more laborious fault management. Also the fault currents are higher and they flow through the ground causing hazard. Thus, the assistance of distribution automation in these cases is valuable.

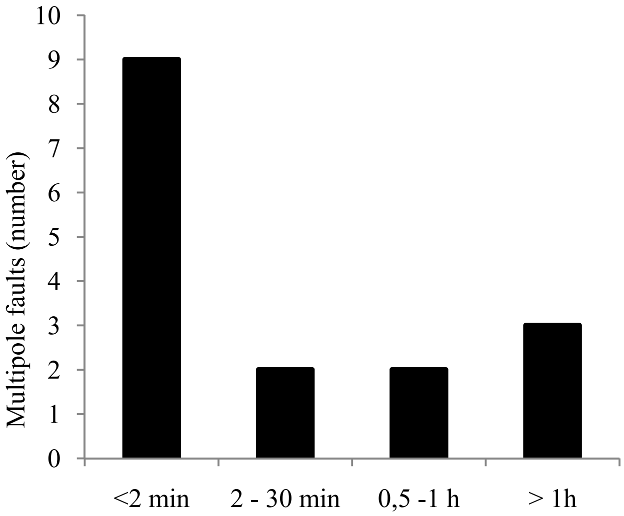

Fig. 8. Frequency of the time when earth faults have evolved into multipole faults, 2004–2010 in the Helsinki 10 kV network.

When compensating is a centralized solution (one compensating unit per one main transformer) distribution automation is, on the opposite, a distributed solution and needs optimization of the most significant secondary substations. The challenge in implementing network automation is how the utility should target the investments so that the cost/benefit ratio is optimum and the decrease in customer interruption cost is the most significant [10]. Theoretically, the layout for network automation can be done by topological and cost-benefit analysis but in real cases many factors are limiting the installation of network automation on secondary substations. The constraints are for example: the age and type of the MV switchgear, insulation material and the ownership of the secondary substation [11]. Helen Electricity Network Ltd. started its network automation undertaking in the year 2008 by a pilot system for the control and monitoring system for urban MV/LV substations. The system includes power quality measurements & database, disturbance recordings, fault location, transformer monitoring and remote control of the MV switches at the substation [12]. By the end of the year 2012 the network automation is implemented to 250 secondary substations in Helsinki.

The development of automatic fault location, restoration and fault mitigation functions in city environment is further studied in task Self Healing City Networks of the Finnish Smart Grid Energy Market program (SGEM). The investments in compensating and in distribution automation affect together to the aim in lowering SAIDI values and in advancing the development of the power system for the benefit of the distribution system operator and also their customers.

IV. Conclusions

The safety issues are the most important aspects in the management of single phase earth faults in the network operation. When considering the operation practices during single phase earth faults, the balancing with customer interruptions and fault clearing processes includes some opposite aspects. The operation with sustained earth faults is possible if the earth fault currents are small enough and the global earthing system is present. To achieve this in wider supply areas a MV network with compensated neutrals is needed. The operation with sustained operation includes advantages, like avoiding major part of the customer interruptions and lowering the earth fault current and transient stresses to substation equipment. However, the disadvantages include the risk of cross country faults and thereafter considerable larger interruption areas and additional repair work.

The paper presented the Helsinki case in the management of earth faults. The main development strategy of Helsinki distribution networks includes a target to halve the SAIDI values down to 6 minutes. The nine years average SAIDI in the Helsinki 10 kV network is already 6 minutes and 13 minutes in the 20 kV network. To be able to lower the SAIDI values of the Helsinki 20 kV network the main means is to allow the operation of the network with sustained earth faults. This is possible when compensating the neutrals. It has been evaluated that this leads to SAIDI level of ca. 6 minutes also in the 20 kV network. So even though some disadvantages caused by sustained earth faults and the needed compensated neutral, Helen Electricity Network Ltd. can achieve the long term development target of halving the SAIDI in coming years. Helsinki has now started to implement compensated neutrals to all 20 kV substations. In addition of this implementation of compensated neutrals, in this work of halving the SAIDI values, the implementation of distribution automation advances the strong network development during the coming years. By the end of the year 2016 Helsinki can have the sustained earth fault operation in the whole medium voltage network and achieve the target in SAIDI. In Helsinki, SAIDI values are already on a very good level. Despite this fact, by this strong development work Helen Electricity Network Ltd. also responds to the strategy of continuous development of the power system.

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VI. BIOGRAPHIES

Osmo Siirto (1962) has received his Master’s degree in Electrical Engineering from Helsinki University of Technology (now Aalto University, Helsinki) in 1990. Since 2009 he has also been a PhD student in Aalto University preparing for his Doctoral Dissertation “Self Healing city distribution networks”. He has been working in many fields of electrical engineering including network planning systems, network control systems, distribution automation and asset management. At present, he is working as Unit Manager of Distribution network at Helen Sähköverkko Oy (DSO subsidiary of Helsingin Energia).

Mika Loukkalahti was born in Kankaanpää, Finland, in 1969. He studied Electrical Engineering at Tampere University of Technology with Electric Power Systems as a major subject. He received his Master of Science degree in 1996. He joined Helsinki Energy in 1997 as Protection Engineer. In Addition to protection systems, Substation automation, Power Quality, network calculation and various expert tasks with network automation and R&D have been his expert and responsible areas. At present, he is leading a group mainly responsible of previous mentioned tasks at Helen Sähkö-verkko Oy (DSO subsidiary of Helsingin Energia). He has been a Finnish Study Committee member of CIGRE B5 (Protection and Automation) Committee since 2006. He has been an active member of several CIGRE B5 working croups, now he is a member of WG B5-43: “Coordination of Protection and automation for Future Networks”. He has also made several presentations in domestic courses and seminars on protection and automation area.

Markku Hyvärinen was born in Sippola, Finland, 1962. He received his Master’s degree in Electrical Engineering and the Doctor of Science (Technology) degree, both from Helsinki University of Technology, in 1988 and 2008 respectively. He has been working in many fields of electrical engineering including substation design, network control systems, protection systems and long term network planning. At present, he is working as Unit Manager at Helen Sähköverkko Oy (DSO subsidiary of Helsingin Energia), Finland, responsible for network development in Helsinki metropolitan area and the related research activities in his company.

Pirjo Heine received the Master of Science degree from Tampere University of Technology, Finland, in 1987 and the Doctor of Science (Technology) degree from Helsinki University of Technology, Finland, in 2005. Her main interests during the university years 1997–2009 were in power quality issues, especially voltage sags of distribution networks. Since 2009, she has been working at Helen Sähköverkko Oy (DSO subsidiary of Helsingin Energia) as a specialist in electrical networks.

Matti Lehtonen (1959) has been since 1999 a professor at the Aalto University, where he is now the head of Power Systems and High Voltage Engineering. His main activities include power system planning and asset management, power system protection including earth fault problems, harmonic related issues and applications of information technology in distribution systems.