TOUCH OF THE CONDUCTOR WITH EARTH SURFACE IN RESONANT EARTHED MEDIUM VOLTAGE SYSTEMS

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ABSTRACT

This paper evaluates the behaviour of physical quantities in the case when electrical conductor under normal operation comes in touch with the earth surface. The main aim of the paper is to perform extensive field-testing and measurement in order to get better insight into phenomena that appear at the place of fault. The newly developed equipment and procedures, required to perform the tests, are presented together with the obtained results.

INTRODUCTION

The reliability of power supply in medium voltage networks is one of the main goals of each distribution company. However, reliability is also expectation and every day needs from the consumers point of view. External factors like weather conditions and aging of the equipment are mostly the main factors, which cause unstable operation of the networks and consequently lead to an insolation breakdown. The insolation breakdowns cause faults in the medium voltage networks. In almost all medium voltage networks the earth faults are the most frequent types of fault. When an earth fault appears, the behaviour and operation of the network depends mostly on the way, how the neutral point is treated. In the resonant earthed systems Petersen coil is deliberately placed between the neutral point of the supplying transformer and the grounding system [1]. The coil is reacting with the reactive current when voltage is applied across the winding. That current opposes the capacitive current due to the capacitance of the network. If the coil is well tuned with the capacitance of the network, the resultant current flowing through the fault place tends to very small values. The significantly low current through the fault place causes a low value of the voltage drop across the grounding system. Therefore, the touch voltage is low and the same is true also for the step voltage. In such circumstances it is possible to operate with the earth fault without tripping for approximately two hours, if the touch voltage remains below 50V. However, the capacitive and inductive currents are not the only currents flowing through a fault place. There exist also higher order harmonic currents that flow through the fault place. Those appear mainly due to the nonlinearity of the system load. Another component of the current through the fault place, which consists of the pure active current, is due to the losses in imperfect insolation of the system [2]. The Petersen coil cannot compensate any of these two current components. Thus, both of them contribute to the increase of true RMS current through the fault place and cause unsuitable condition for the arc suppression. In a real operation it is possible that conductor of the overhead line comes in touch with the earth surface. In such particular occasion it is normally unknown what exactly is going on. It must be pointed out that in real operation the fault place and the condition at the fault place are unknown in most cases. The main goal of the presented paper is to get a deeper insight into the phenomena and factors that influence these phenomena at the fault place in the case when the overhead line under normal operation comes in touch with the earth surface. This is done through the experiments and measurements performed in a medium voltage network under normal operation. The analysis of obtained results makes possible to get a better insight into phenomena and their behaviour at the fault place.

DESCRIPTION OF THE DISCUSSED SYSTEM

The field-testing was performed in the transformer substation RTP Krško operating under normal conditions as an apart of real distribution network. The high voltage (HV) supply level is 110 kV while the distribution level is medium voltage (MV) 20 kV. A transformer (TR) with rated power 40 MVA is applied to transform the energy from the HV level to the MV level. This transformer supplies the MV busbar onto distribution feeders are connected. The entire length of the connected feeders is around 253 kilometres. Share of the overhead lines is 83 percent while the share of the underground lines is 17 percent. The system consists of six radial distribution feeders, which supply 248 transformer substations. The voltage transformation level is 20/0.4 kV and the entire installed apparent power is 32.6 MVA. The neutral point (N) of the 40 MVA supply transformer is connected through controlled variable inductor [3], so called Petersen coil (PC), to the ground system (E). The shunt resistor (R) is used to increase the watt-metric component of the fault currents. The connection of the shunt resistor is achieved through the switch (S) while the value of the resistor is 1 Ω. The applied experimental setup is schematically presented in Fig. 1. Flexible conductor, which has been used to simulate the touch with the earth surface, is supplied trough the feeder J03. The line-to-neutral voltages u_{L1}, u_{L2} and u_{L3} are measured on the voltage transformers VT1. The residual voltage u_e is also measured on the same voltage transformer.

The ring current transformer CT1 is applied to measure the current i_L trough the Petersen coil. The voltage on the fault place u_f is measured with the voltage transformer VT2 while the current through the fault place i_f is measured with the ring current transformer CT2.

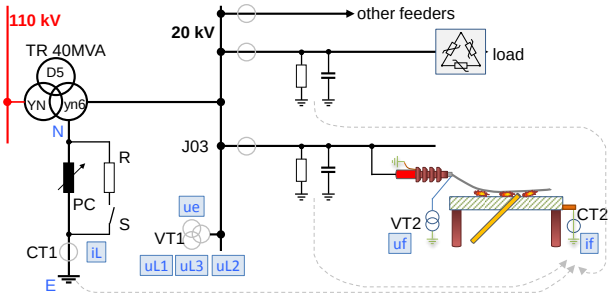

Figure 1: Discussed system presented schematically

The feeders supply different kind of loads, from the linear ones to the nonlinear ones. The nonlinear loads cause harmonic distortion of the measurement signals and the presence of the higher order harmonic components in the fault current. All current and voltage measurement chains were connected to the data acquisition unit DEWE5000 in order to record the instantaneous values of currents and voltages during performed experiments.

EXPERIMENTAL SET-UP

The experimental set-up, schematically shown in Fig. 2, makes possible to control movement of the flexible conductor up and down above the earth surface. This is achieved with the help of an insulated stick. The flexible conductor is connected to the voltage U_{L1} of the phase L1 through the supply cable. An aluminium box is filled with the soil and earthed through the current transformer, which is used to measure the current I_f through the fault. The voltage transformer is used to measure the voltage U_f over the fault. The experimental set-up was applied to perform experiments and measurements in a resonant earthed system with the total capacitive current around 100 A. The system was overcompensated for ten percent. The amount of voltage asymmetry in the resonant point was 4.8 percent.

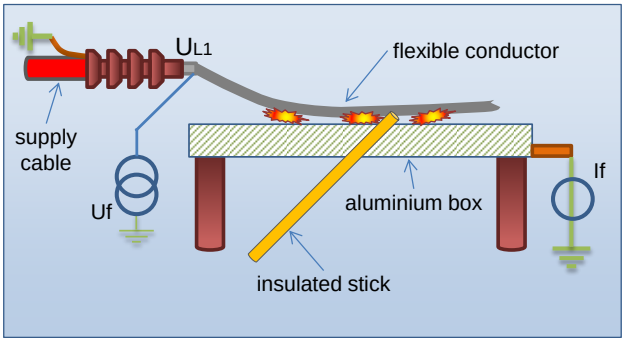

Figure 2: Equipment for measurement at the fault place

The complete cycle of sweep down and raise up was performed. Figure 3 shows a photograph taken at the moment when the conductor moved down just before it has touched the earth surface.

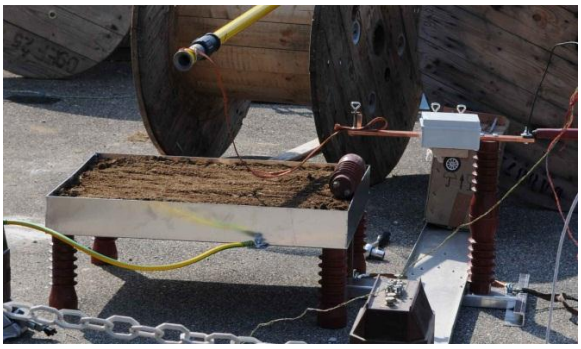

Figure 3: Moment before the conductor touched the earth surface

Figure 4 shows the photograph taken at the moment when the conductor has touched the earth surface. At the same moment an arc was ignited. In this particular time the shunt resistor switch S (Fig. 1) was still disconnected.

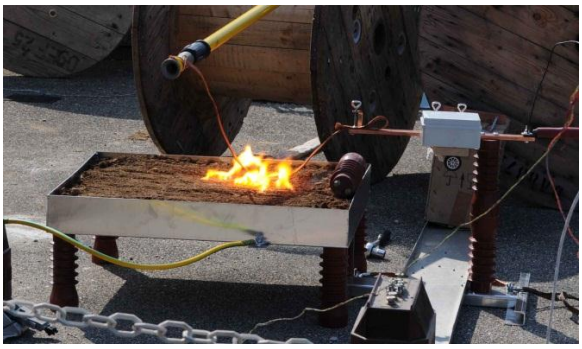

Figure 4: Moment when the conductor came in touch with the earth surface and the shunt resistor R (Fig. 1) was off

Figure 5 shows the moment when the conductor started to move up from the earth surface. At this time the switch S (Fig. 1) was closed and the current through the fault place was increased.

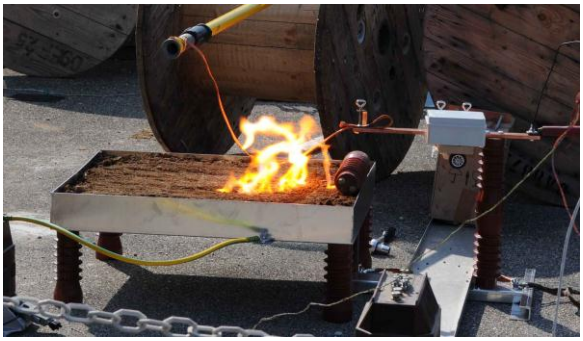

Figure 5: Moment when conductor started to raise up from the earth surface and shunt resistor R (Fig. 1) was on

After a few seconds at such operation the watt-metric protection disconnected the faulted feeder.

MEASUREMENT RESULTS

During the experiments the data was captured with data acquisition unit DEWE5000 with the sampling frequency of 10 kHz. The measured results were converted and imported in Matlab for further analysis. The instantaneous values of currents and voltages measured during the experiments were used to calculate the RMS (root mean square) values. The RMS values of current $I(t)$ and $U(t)$, are given by (1) and (2):

$$I(t) = \sqrt{\frac{1}{T}\int_{t-T}^{t} \mathbf{i}^{\mathrm{T}}(\tau)\mathbf{i}(\tau)d\tau} \quad (1)$$

$$U(t) = \sqrt{\frac{1}{T}\int_{t-T}^{t} \mathbf{u}^{\mathrm{T}}(\tau)\mathbf{u}(\tau)d\tau} \quad (2)$$

where the time interval of interest is given as $[t\text{-}T, t]$ while **u** and **i** denote the vectors of samples of individual line currents and voltages.

Figure 6 shows the waveforms of the line to ground voltages u_{L1}, u_{L2}, u_{L3} and the corresponding RMS values U_{L1}, U_{L2}, U_{L3} on the 20 kV system busbar. The moment when the conductor touches the earth surface is marked with the CT arrow. Before the fault appears, the RMS voltages are around 12 kV as shown in Fig. 6. When the conductor touches the earth surface, the voltage in the faulted phase L1 starts to collapse down to 6 kV while the voltages of the healthy phases L2 and L3 starts to rise toward 19.9 kV and 15 kV, respectively.

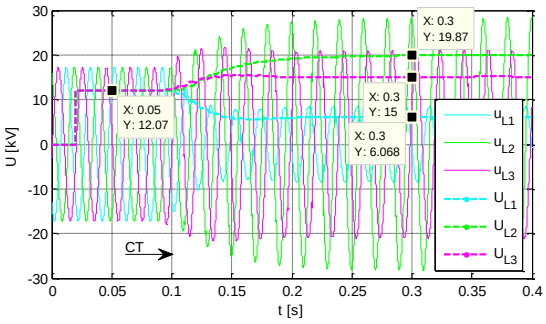

Figure 6: Voltage waveforms u_{L1}, u_{L2}, u_{L3} and RMS values U_{L1}, U_{L2}, U_{L3} on the 20 kV system busbars

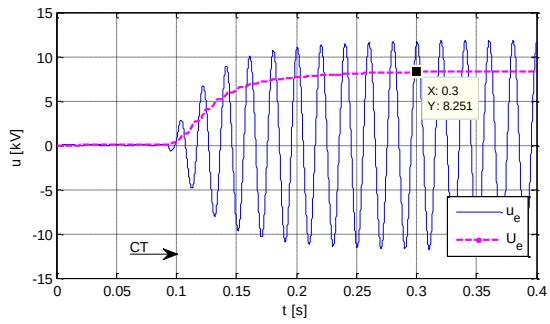

Figure 7: Waveform of the residual voltage u_e and its RMS value U_e

Immediately after the conductor touches the earth surface, the residual voltage U_e starts to rise and achieved 8.3 kV after 300 ms, as shown in Fig. 7.

The residual voltage u_e that appears across the Petersen coil causes the current i_L through the coil. This current lags behind the residual voltage for approximately $\pi/2$ and opposes the capacitive current of the entire system. For the discussed case, the current i_L with RMS value of 80.7 A is shown in Fig. 8. It depends on the momentary adjustments of the coil.

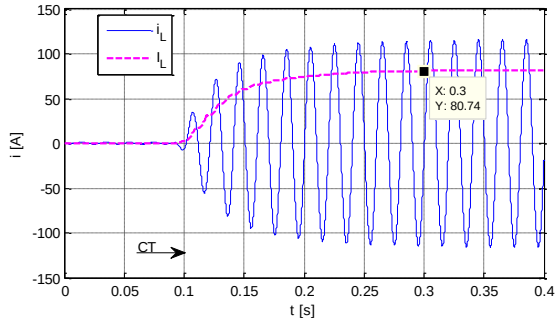

Figure 8: Waveform of the current trough the coil i_L and its RMS value I_L

Figure 9 shows the voltage u_f across the fault place. When the conductor is up the voltage is 12 kV RMS. After ignition of the arc, caused by the touch of conductor with earth surface, this voltage falls to 6 kV RMS.

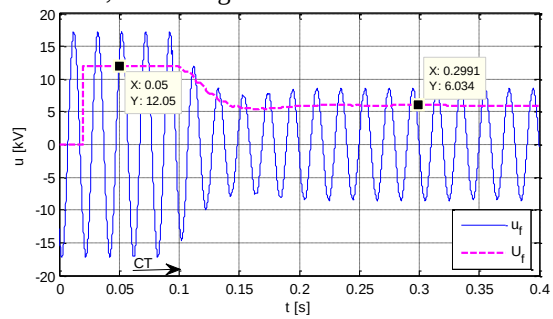

Figure 9: Fault voltage waveform u_f and its RMS value U_f

Fig. 10 shows that immediately after the conductor touches the earth surface, the current through the fault place i_f starts flowing and reaches 6.7 A RMS.

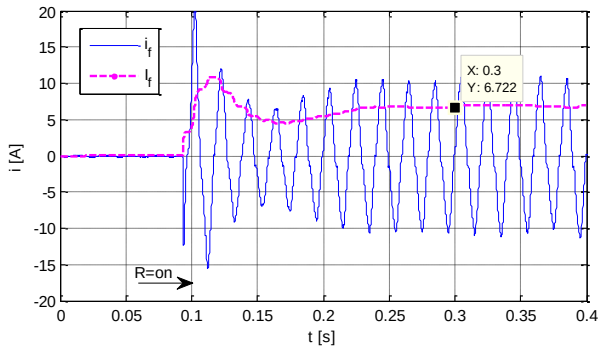

Figure 10: Waveform of the current trough the fault place i_f and its RMS value I_f

The Petersen coil completely compensates the capacitive component. Due to the 10 percent over compensation of the coil, the fault current consists of the residual coil current, the uncompensated watt-metric components, and the uncompensated higher order harmonic components. From the current i_f shown in Fig. 10 it can be concluded that the arc is very stable and varies very little with the time.

The next few figures are used to show the impact of the shunt resistor R connected in parallel to Petersen coil, as shown in Fig. 1, on the measured results. The main goal of the resistor is to increase an active component in the fault current. This helps the protection system to detect easily and more accurately the faulted feeder, and increases protection system sensitivity and reliability. Fig 11 shows the residual voltage u_e before and after the resistance R is switched on. The position when the switch S (Fig. 1) is closed is marked with arrow R=on in Figs. 11 and 12. It can be see that the residual voltage U_e decreases from 9.4 kV RMS to 6 kV when resistor R is connected in parallel with the Petersen coil.

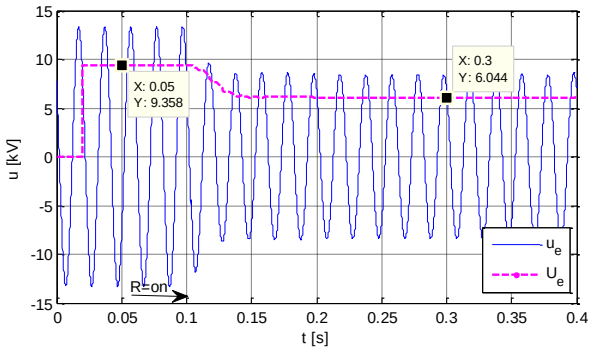

Figure 11: Waveform of the residual voltage u_e and its RMS value U_e for switching on the resistor R

Voltage on the fault place is approximately equal to the difference between faulted phase voltage and the residual voltage. Therefore we can expect a slight rise of the voltage through fault place. The same is true for fault current too, because the arc is mostly determined with ohmic character. Fig. 12 shows the current through fault place before and after the shunt resistor is switched on, and confirms previous statement.

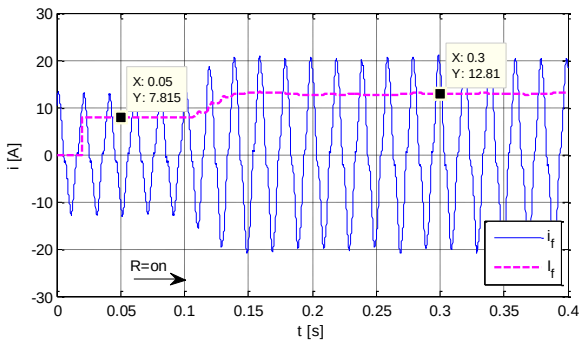

Figure 12: Waveform of the current trough the fault place i_f and its RMS value I_f for switching on the resistor R

Fig. 13 shows the amplitude spectra of the current i_L through the Petersen coil. The impedance of the Petersen coil increases while the impedance of the network capacitance decreases with the increasing frequency, which can be clearly seen in Fig. 13. The amplitude spectra of the coil current i_L contains almost no higher order harmonic components. On the contrary, the fault current i_f contains a substantial share of higher order harmonic components. The capacitance of the systems offers the higher harmonic components much easier path for closing harmonic currents through the fault place. Thus, the fault current contains harmonic components of the order 3, 5, 7,… not existing in the coil current.

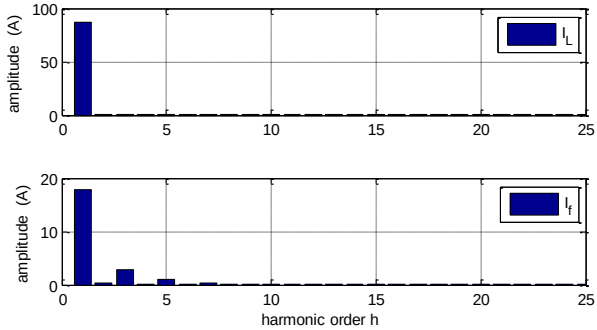

Figure 13: Amplitude spectra of the coil current i_L and fault current i_f

CONCLUSION

The results presented in this paper clearly show that the arc ignites immediately after the conductor touches the earth surface. Intensity of the arc depends on many conditions at the fault place, like humidity, wind, snow, coil adjustments, etc. However, it can be concluded that under normal operating conditions the arc is relatively stable and has enough energy to cause a fire on dry surface at the fault place. It can be also concluded that a touch and step voltage are not critical as long as the earthing system resistance is low enough. A possibility to touch a conductor when lying on the ground surface is one of the most dangerous situations that must be treated extremely carefully. According to the results of experiments it can be concluded that even a perfectly tuned and fully compensated Petersen coil cannot completely compensate the fault current. The remaining higher order and active current components in the fault current are sufficient to sustain the arc.

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