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NUMERICAL SIMULATION OF DISTANCE PROTECTION ON THREE TERMINAL HIGH VOLTAGE TRANSMISSION LINES

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Abstract: Transmission lines are protected by special devices called distance numerical protection relays. The presence of a T-connection on a third terminal transmission line can drastically affect the performance of a distance relay at other terminals. The paper presents modeling and simulation of numerical distance protection relays using *DIgSILENT* software on real three terminal (T-terminal) 110 kV transmission lines. A sample case of a part of 110 kV, high voltage transmission network in HEP TSO Transmission area Zagreb, which includes a section of T-terminal transmission line is analyzed. Three phase and single line to ground faults were simulated on each 110 kV transmission line section, and a time response of polygonal characteristic of numerical distance relay was presented.

Keywords: *Distance numerical protection, three terminal line, apparent impedance, computer simulation, DIgSILENT PowerFactory software*

1 INTRODUCTION

A digital distance relay uses sampled voltage and current data from the relaying point for measuring the apparent impedance and then uses an appropriate characteristic to make proper decisions to disconnect a faulted line. Because different network conditions correspond to different remote-end infeed/outfeed behavior and since this is not measurable at the relaying point, the traditional distance relays have faced severe static underreach and overreach problems. In general, the first zone reach of a non-pilot distance relay is set to cover 80-90% of the line length to the nearest remote terminal to avoid relay overreach under all operating conditions. The relay, however, may not even extend beyond the tee point in some under-reaching cases [1]. Recently, the adaptive relaying concept has brought hope that a solution for solid faults could be developed. This paper simulates relay-reach coverage problems caused by the second and third terminal infeed/outfeed effects under different fault conditions. The paper will present one easy to use, window based simulation tool for power system fault analysis integrated with coordination and simulation of protection devices. Computer simulations profile the infeed/outfeed behavior variations for different fault resistances and pre-fault conditions [2].

2 FUNDAMENTALS OF DISTANCE PROTECTION

Distance protection represents the most widely used protection in both high voltage networks and extra-high voltage networks. Distance relays are complex devices which measure the voltage and current at a fault location and determine their relationship:

$$t_{d\delta} = k\frac{U}{I} = kZ_k = kZ_1 L_k = k_i L_k \quad (1)$$

L_k - distance of the relay to the fault location

The operating time of the distance relay is proportional to the distance from the fault location. Less distant faults are switched off in the shortest time and vice versa ($t_r \cong k_2 L_k$). Since relays measure impedance, they are called impedance (resistance) relays. Distance relays consist of more elements-stages.

2.1 Distance protection principle

Distance protection determines the fault impedance from the short-circuit voltage and current at the location where the relay is installed (Fig. 1).

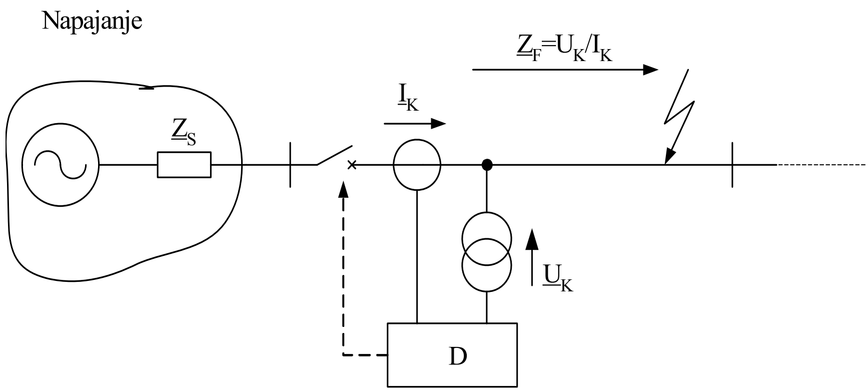

Fig. 1. Distance protection principle, measurement of fault impendence

The measured fault impedance is compared with the known line impedance. If the measured fault impedance is smaller than the set line impedance, a fault is detected and a trip signal sent to the circuit-breaker. This means that the distance protection in its simplest form operates by measuring the voltage and current at the relay location. No additional information is required for this basic distance protection, and the protection does not have to depend on any additional equipment or transmission signal. Because of inaccuracies in distance measurement, which are the result of measurement errors, transformation errors and inaccuracies in line impedance, in practice it is impossible to set the protection to 100% of the line length. A security limit (10 % -15 %) from the end of the line must be determined for the so-called under-reaching zone (1st zone) in order to ensure protection selectivity due to internal and external faults, which can be seen in Fig. 2. The rest of the line is covered by an over-reaching zone (2nd zone) which, in order to ensure selectivity, must have a time delay with respect to the protection of the neighboring line. In the case of an electro-mechanical protection, this difference in time is 400-500 ms, and 250-300 ms in the case of analog static and numerical protection. This time delay includes the operating time of the circuit-breaker, delay of the distance measuring elements as well as the security limit.

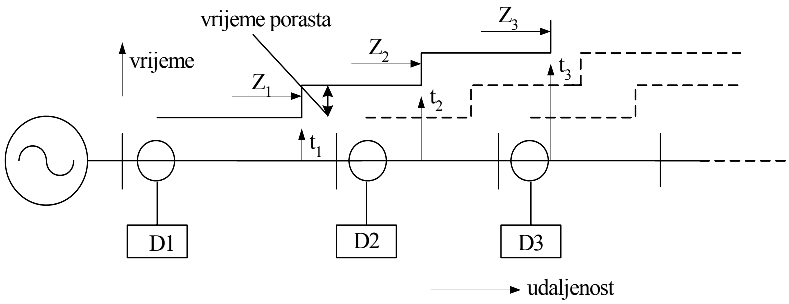

Fig. 2. Distance protection principle, division of the distance grades

In contrast to differential protection which is completely selective (its protection zone is entirely defined by the location of the current transformers at both line ends), the distance protection in its simplest form (without telecommunication supplements) does not provide absolute selectivity. Selective tripping must be ensured by time delay relative to the neighboring protection. However, distance protection has the possibility of reserve protection for the neighboring lines. The second stage (over-reaching stage) is used for this purpose. It reaches the neighboring busbars and a part of neighboring lines. The next, 3rd stage is usually used for protecting the entire length of the neighboring lines (Fig. 2). The arrangement of the stages and time settings is obtained with a t-I diagram.

2.2 Relay impedance

Distance protection relays are so-called secondary relays fed with current and voltage measured signals from the primary system (overhead line) via measurement transformers. Therefore, the relay measures the secondary impedance resulting from the ratio of current transformation and voltage transformers.

$$Z_{sec} = \frac{I_{prim} / I_{sec}}{U_{prim} / U_{sec}} Z_{prim} \tag{2}$$

t-I diagrams are usually done with primary impedances. Furthermore, the relay settings are done with secondary impedances if the testing of the relay is carried out with a secondary signal. As a result, the relay impedance values must be calculated using equation (2).

2.3 Impedance diagram

To the protection engineer, the impedance diagram is the most important tool for the evaluation of the behavior of distance protection. In this diagram, the relay characteristic, measured load and short-circuit impedance are represented in a complex R-X plane. During normal operation, the measured impedance corresponds to the load impedance. The value is inversely proportional to the transferred load ($Z_{load}=U_{line}^2/P_{load}$). The angle between voltage and current corresponds during that time to load angle φ_T (Fig. 3.). It depends on the ratio between the active and reactive power (φ_T =arc tg P_Q/P_A]). During fault, the measured impedance becomes short-circuit impedance, which is smaller than the load impedance. Its value corresponds to the line impedance between the relay and fault location.

If transient resistance is present at the fault location, arc resistance (R_L) is added to the line impedance parallel to the R-axis. The angle that is now measured between the current and short-circuit voltage is the short-circuit angle (φ_K). The operating characteristic of distance protection is defined by the shape in the impedance diagram where the fault area is isolated from the load area as well as distant stage ranges. Ultimately, a direction characteristic defines two impedance areas depending on the direction measured by the relay. The relay impedance characteristics are geometric forms composed of straight lines and circles. A typical example of a distance relay is given in Fig. 3.

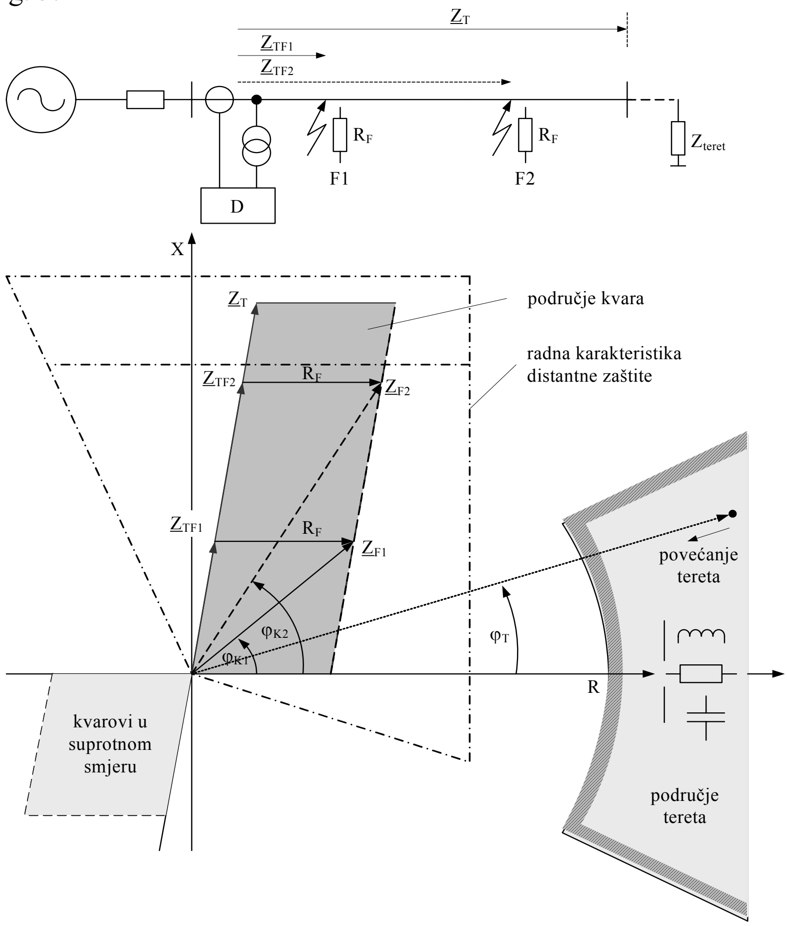

Fig. 3. Load and short-circuit impedance

2.4 Starting

The initial task of the starting element is to detect and classify short-circuits in the network. It has to be phase selective, i.e. it has to correctly recognize the faulted phase without incorrect starting in any of the healthy phases. This is very important during single-phase faults in order to ensure selectivity of single-phase tripping, where single-phase automatic reconnection is used. In the case of distance relays with only one measuring element, the starting element controls the sequence of process of the measured values.

2.4.1 Over-current starting

It is the simplest and fastest method for fault detection. It can be applied when there is a sufficiently large short-circuits current flow. Because of that, the short-circuit current should not be less than twice the maximum load current. The setting should be approximately 1.3 of the maximum load current per phase and 0,5 I_N (secondary current of the current transformer /CT) for zero current component. For parallel lines, it should be taken into account that, when one line is out of service, the other line can conduct twice the current, at least for a short time. In that case, the phase settings must be doubled. Furthermore, it must be known that in earthed systems the occurrence of the zero current components is not sufficient for the starting. Also, for correct loop selection, the short-circuit current must be large enough in the corresponding phase. In order to check the reliability of fault detection, a two-phase fault must be used because its fault current is smaller for $\sqrt{3}$ if compared with the three- phase fault. Moreover, in the earthed network, the single-phase short-circuit current must be checked and calculated.

2.4.2 Under-impedance starting (U< i I>)

Due to the following, the short-circuit current on a line can be too small to cause the starting:

- weak source (high source impedance)
- the current is directed to parallel paths in a meshed system
- limitation of the zero current component by resistance and reactance in the transformer star point.

In these cases, voltage monitoring is a useful additional condition for the starting. Voltage at the relay location depends on both, the source impedance and fault impedance (fault distance) that can be seen in Fig. 4.

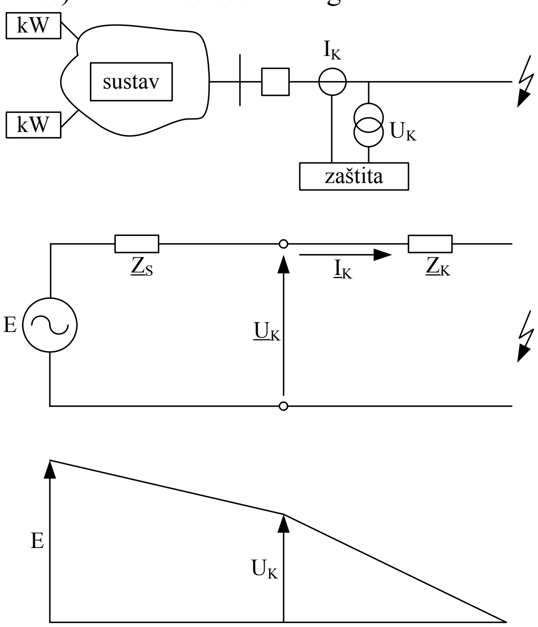

Fig. 4. Voltage at the relay location during short-circuit

In order to prevent incorrect starting when the line is isolated (no voltage), the under-impedance criterion is combined with a low-set (0,2 I_N - 0,5 I_N) current hold on current i.e. the under-impedance starting is possible when the minimum current flows. In the case of under-impedance starting, the voltage is controlled by the current so that the sensitivity of starting voltage decreases along with current decrease. Fig. 5. represents the resultant starting characteristic.

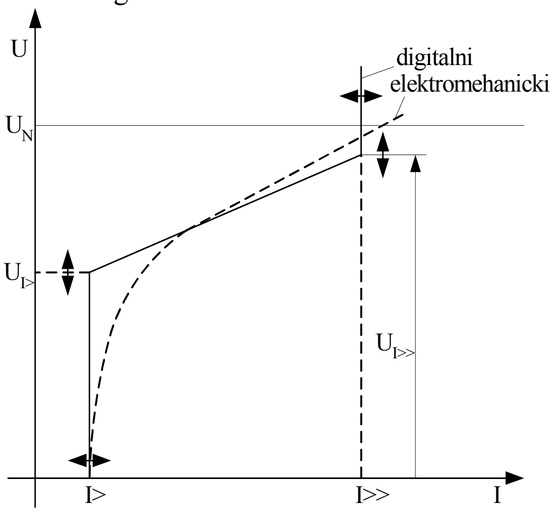

Fig. 5. Under-impedance starting

In this case I>> corresponds to the over-current starting stage. The typical setting is: I>=0.5 I_N , I>>=2.5 I_N and U(I>)=0,7 U_N as well as U(I>>)=U_N.

2.4.3 Impedance starting

As shown in Fig. 3, the impedance characteristic can be appropriately set to distinguish between the fault and load conditions. In this case, all six possible fault loops (L1-E, L2-E, L3-E, L1-L2, L2-L3, L3-L1) are continuously measured or calculated as well as monitored by using numerical technology. In the case of conventional relays, the starting characteristic is already optimized using different circular characteristics and lines, which is shown in Fig. 6.

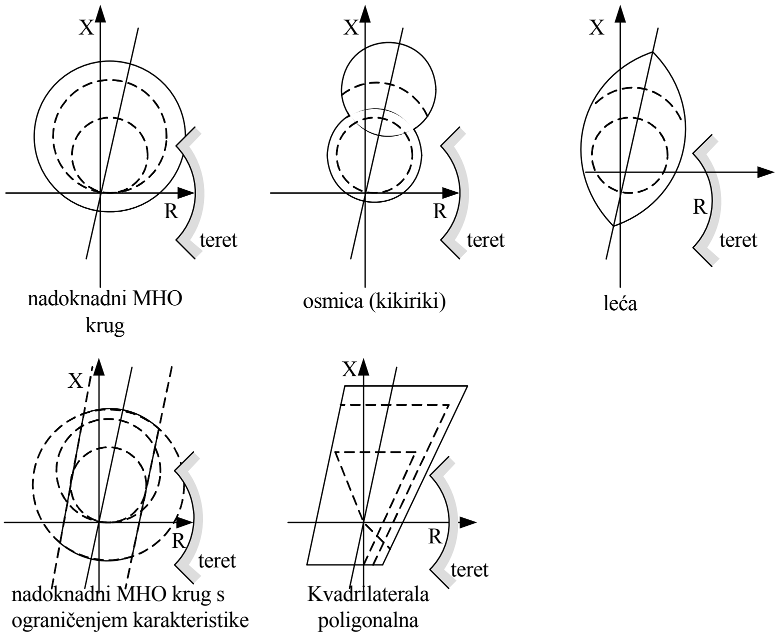

Fig. 6. Starting impedance with conventional technology

Here, we search for the following:

- large reach in X-direction for the detection of remote faults
- sufficient arc compensation in R-direction while maintaining secure limits for the purpose of preventing the extension to the load area.

3 NETWORK MODELING AND FAULT SIMULATION

Network modeling and fault simulation was implemented in *DIgSILENT PowerFactory 14.0.*, a version developed by engineers and programmers that have a years-long experience in power system analysis. The software, which has an integrated graphical user interface, is used for power system analysis. The integrated interface includes drawing functions, editing functions, and all relevant static and dynamic calculations. For the purpose of network modeling, both, current transformers **600A/1A** and voltage transformers **110 000V/100V** were used.

3.1 Network modeling

The modeled network consists of three sources, a busbar and a line that forms the T-point. At the bottom of the window the TS Mraclin busbar is located; TS Resnik is in the upper part of the window, while TS Dugo Selo is on the right part of the screen (see Fig. 7.).

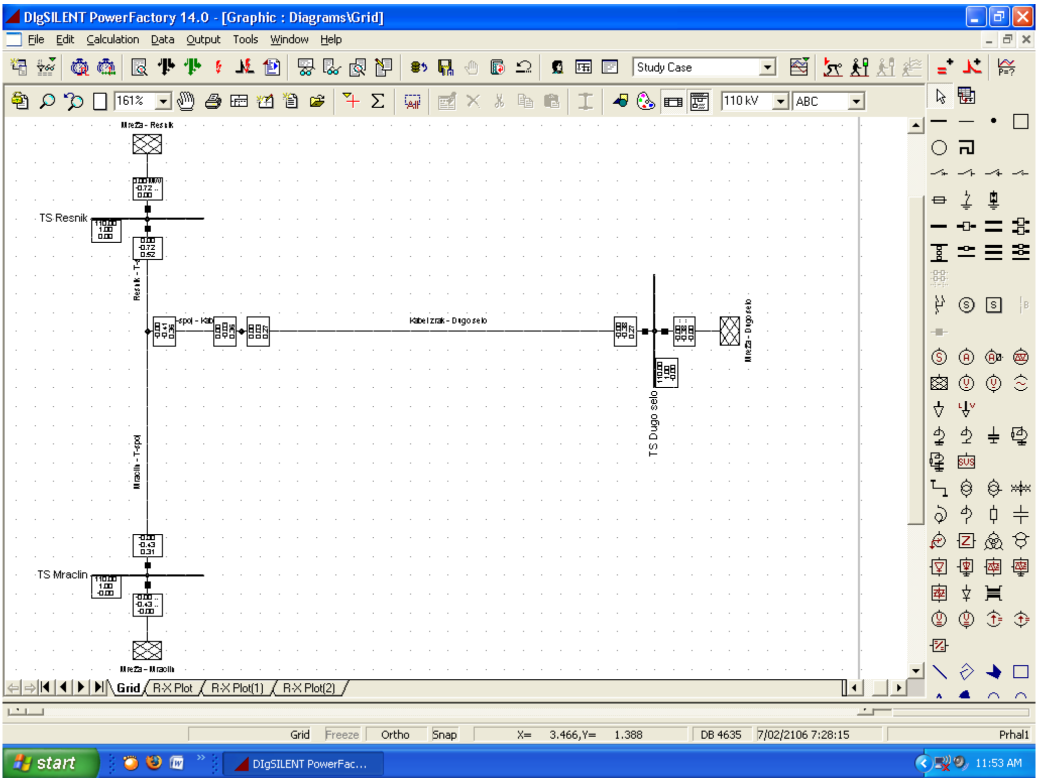

Fig. 7. T-point: TS Mraclin – TS Resnik – TS Dugo Selo

The original network, which has been modeled, is the entire network of the city of Zagreb and its wider area, which corresponds to the Thevenin equivalent, i.e. T-point in which all the data obtained from the database of HEP TSO Transmission Area Zagreb have been entered. A three-phase fault on the busbars has been modeled and simulated, while the electricity values *Ik“max* have been entered into the modeled network. Thus the input data have been obtained which correspond to the equivalent original network. Fig. 8. - Mraclin;   Fig. 9. – TS Resnik; Fig. 10. – TS Dugo Selo.

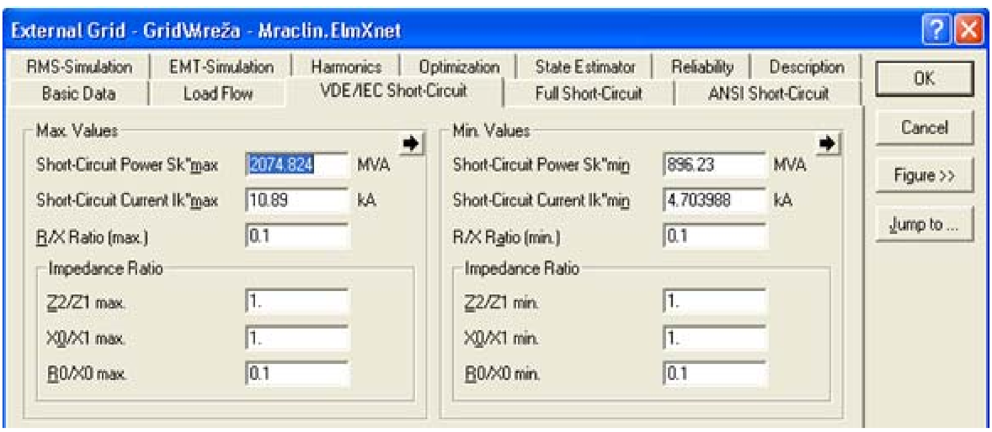

Fig. 8. TS Mraclin

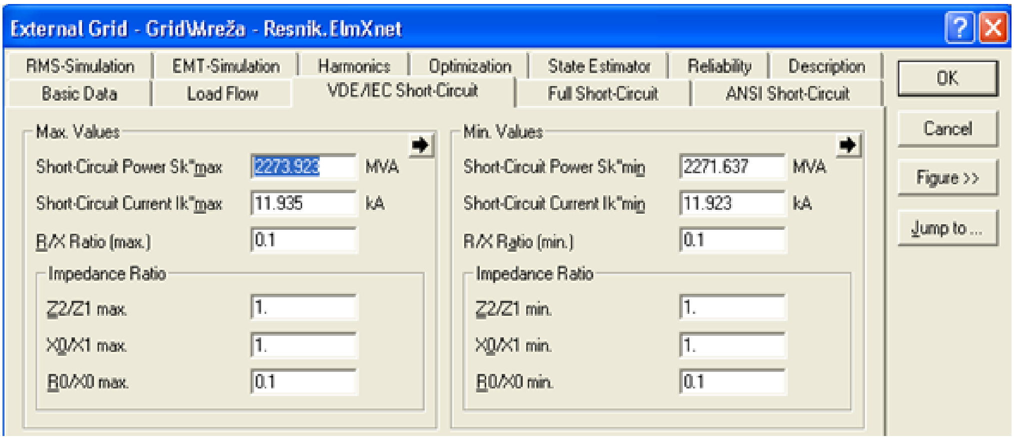

Fig.9. TS Resnik

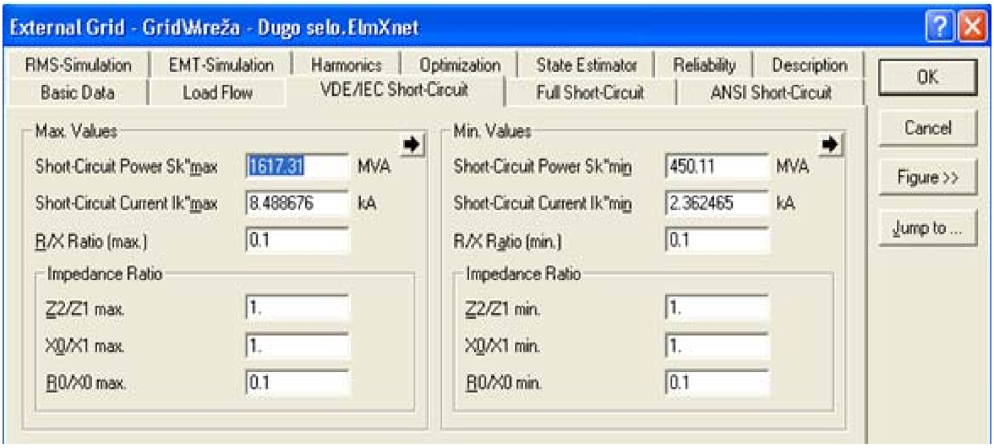

Fig. 10. TS Dugo Selo

Modeling of the 100 kV terminal was taken from the existing DIgSILENT database. Furthermore, lengths for each terminal have been entered, and the per-unit reactance (X1) has been checked, i.e. it has been checked whether it corresponds to the set values obtained from HEP TSO. The values are shown in Fig. 1.

3.2. Modeling of the three-phase fault

Fault modeling in *DIgSILENT PowerFactory 14.0* is executed by clicking the right-mouse button on the desired line. Then, the dialog box shows up and we click on **Calculate** and then **Short-Circuit.**

After that, a menu where we can choose the type of short-circuit or fault shows up, as well as the location where the short-circuit is to be simulated.

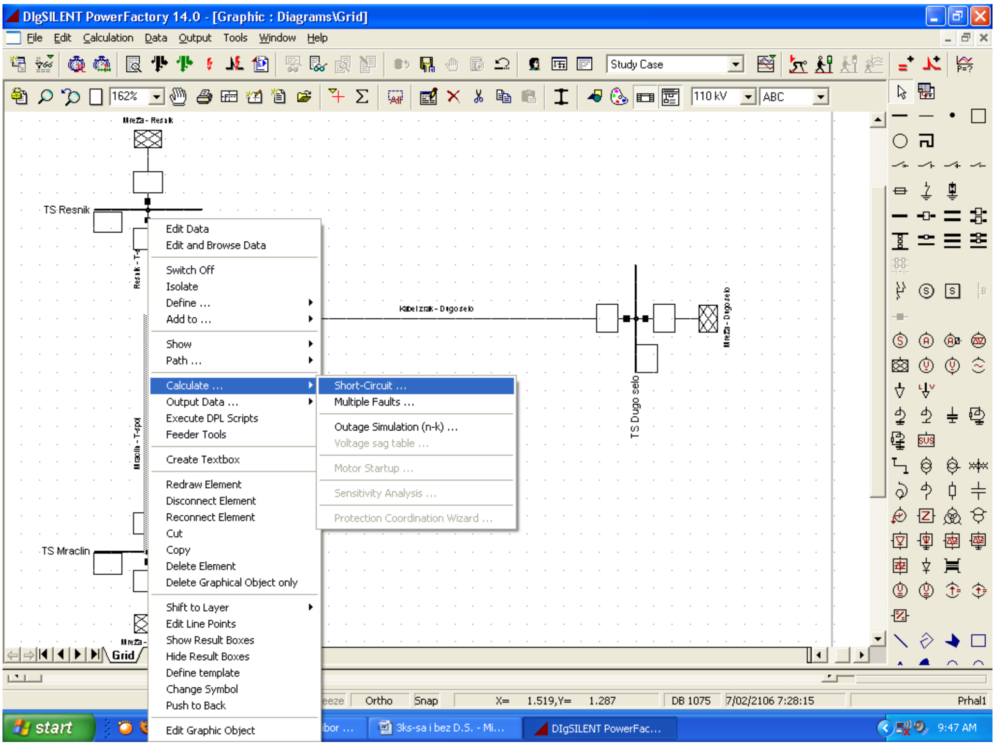

Fig. 11. Dialog box

4 THREE TERMINAL TRANSMISSION LINE

Systems A, B and C represent the three external equivalents and L_{AT}, L_{TB}, and L_{TC}, are the three line sections of the three-terminal line shown in Fig. 12 [3]. The simulation was performed on real 110 kV transmission three terminal lines in HEP TSO Zagreb on high voltage network which connects 110 kV transformer stations Resnik, Mraclin and Dugo Selo.

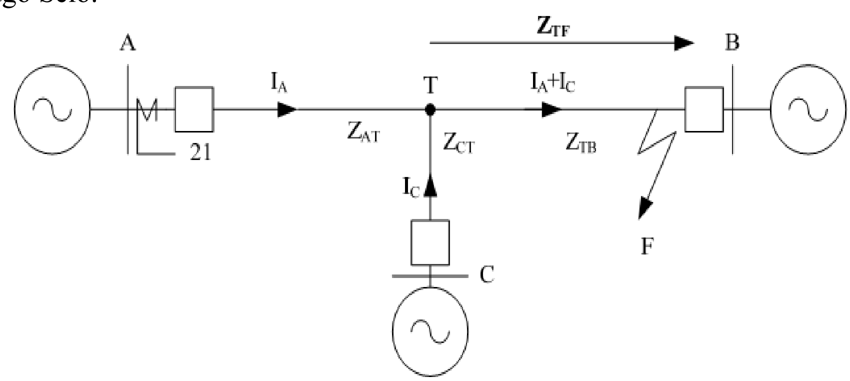

Fig. 12. Three-terminal line with the external systems

The distance relays ABB REL 511, SIEMENS 7SA 511 and the latest technology SIEMENS 7SA 6xx are placed in TS Mraclin, TS Resnik and TS Dugo Selo, respectively. All network components, lines, busbars, external network equivalents and time-impedance settings for all three distance relays are modeled in *DIgSILENT* software in appropriate dialog boxes according to real data [4]. The three-phase and single line to ground fault are simulated in all three sections, and then R-X plots for ABB and SIEMENS distance relays are plotted. In the first case, we can see that the distance relay will act in the first impedance zone in the fastest time.

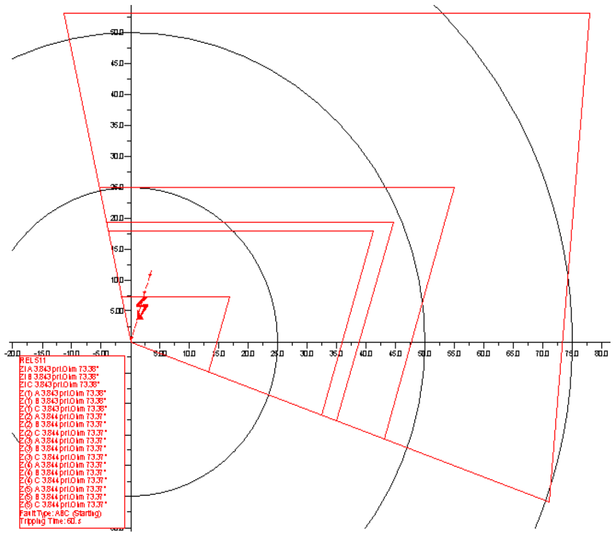

Fig. 13. The R-X plot for three-terminal line faulted at 50% of section TS Mraclin – T-point relay REL511

Characteristic of R-X Plot –in TS Resnik; we have used the Siemens 7SA511 relay. The three-phase fault is at the distance of 12.135km from the relay.

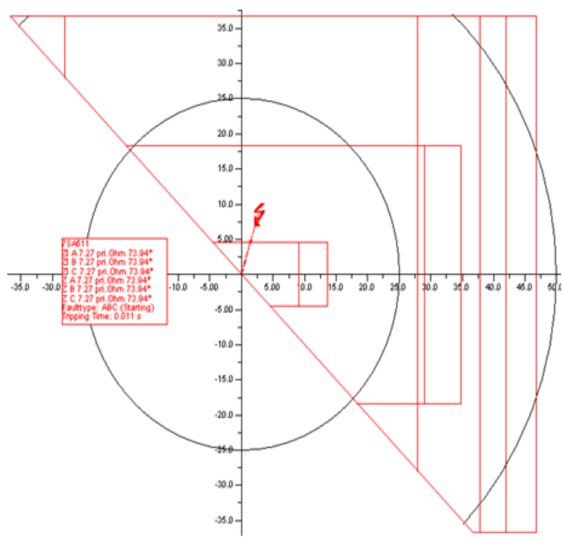

Fig. 14. The R-X plot for three-terminal line faulted at 50% of section TS Resnik – T-point relay 7SA511

Characteristic of R-X Plot –in TS Dugo Selo; the Siemens 7SA6xx relay has been used. The three-phase fault is at the distance of 14.55km from the relay.

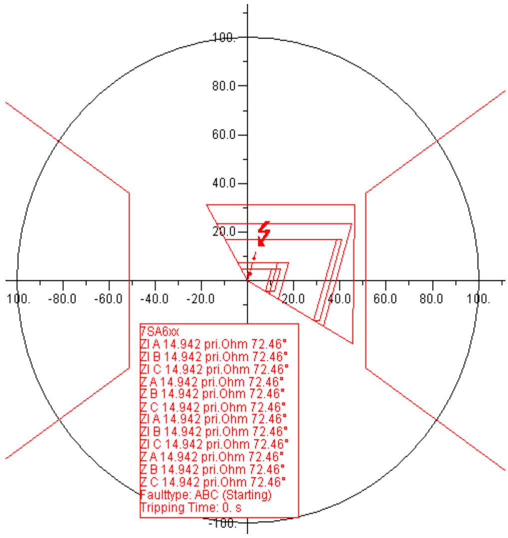

Fig. 15. The R-X plot for three-terminal line faulted at 50% of section TS Dugo sleo – T-point relay 7SA6xx

Since the three-phase fault is the nearest to the REL511 relay (TS Mraclin), this relay is the first to detect the fault and to clear it. As shown in Fig. 13, the fault is cleared in the 1st zone. If it were not so, it would mean that the relays were incorrectly adjusted. At the length from the fault, the 7SA511 relay is located in Resnik. The 7SA511 relay will clear the fault in the 2nd zone (Fig. 14). On the other hand, the 7SA6xx relay located in TS Dugo Selo, which is the remotest location relative to the fault, will also clear the fault in the 2nd zone, however, first at the end of the 2nd zone. It can be concluded that the remotest relay requires the longest response time (Fig. 15).

4.1 Three-terminal line faulted at 50% of segment TS Resnik – T-point

The three-terminal line faulted at 50% of the segment TS Resnik-T-point is at a distance of 50 %, i.e. 1.485 km from TS Resnik, in contrast to TS Mraclin which is 19.825 km remote from the three-phase fault. The distance between TS Dugo Selo and the three-phase fault is 12.255 km.

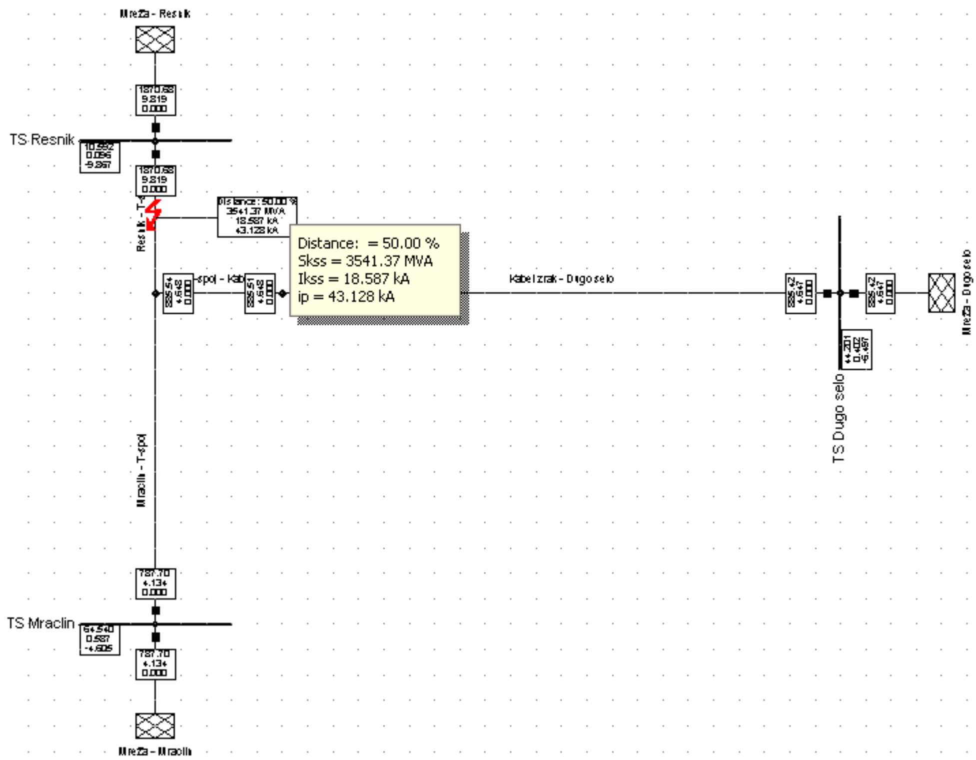

Fig. 16. Three-terminal line faulted at 50% of the segment TS Resnik-T-point

Characteristic of R-X Plot – in TS Mraclin, i.e. ABB REL511 relay; the three-phase fault is at the distance of 19.815km from the relay.

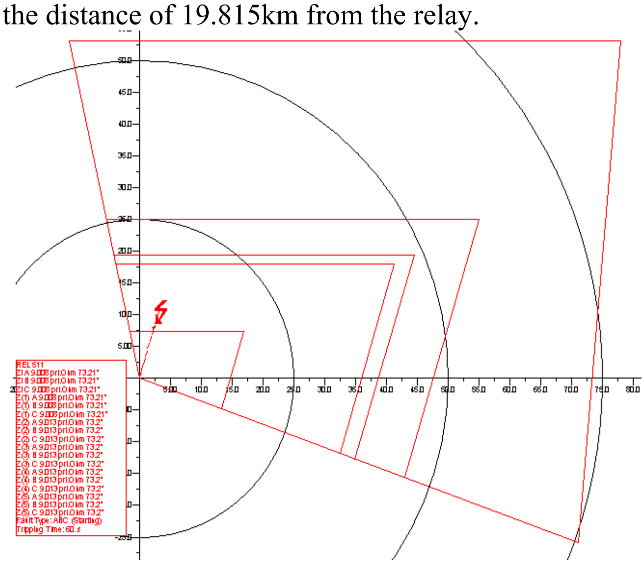

Fig. 17. REL511, TS Mraclin

Characteristic of R-X Plot – in TS Resnik; Siemens 7SA511 relay; the three-phase fault is at the distance of 1.485km from the relay.

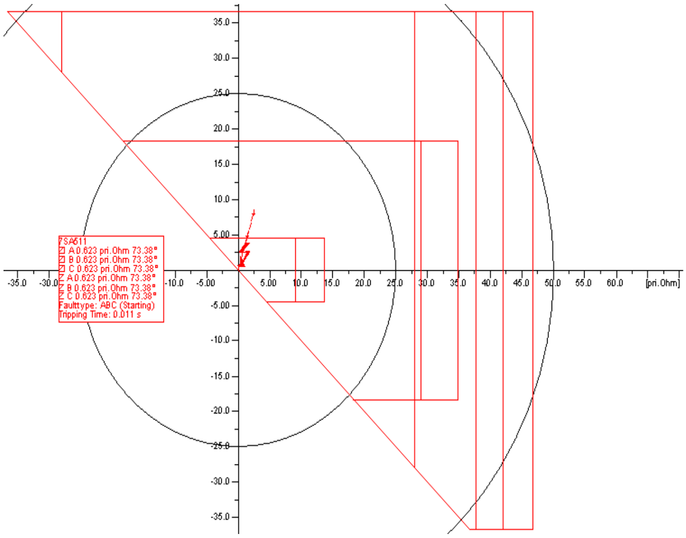

Fig. 18. TS Resnik - 7SA511

Characteristic of R-X Plot - in TS Dugo Selo; Siemens 7SA6xx relay; the three-phase fault is at the distance of 14.55km from the relay.

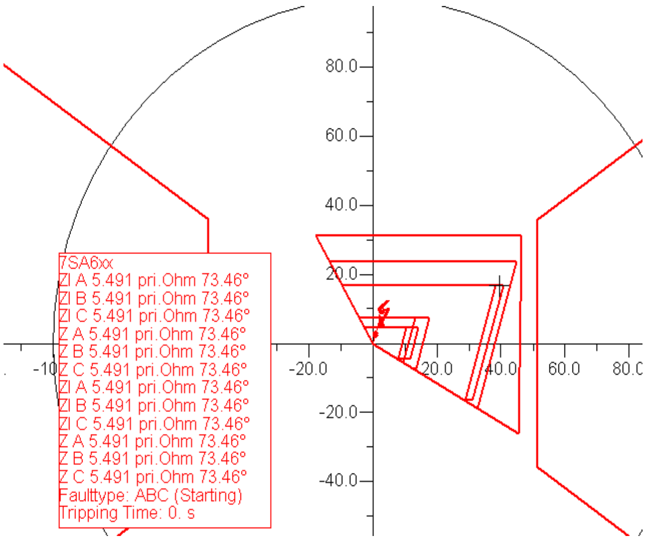

Fig. 19. TS Dugo selo – 7SA6xx

The relay in TS Mraclin, i.e. REL511, will switch off in the 2nd zone due to its remoteness. This is normal because the closer relay must be switched off (Fig. 17). The relay that will be switched off in the 1st zone is the 7SA511 relay, i.e. the relay in TS Resnik, as can be seen in Fig. 18. The relay, which is located in the overlapping zones of the 1st and 2nd zone, is the relay in TS Resnik (Fig. 18). The relay located within the overlapping zones of the 1st and 2nd zone is relay 7SA6xx TS Dugo Selo, which, however, will not respond in the 1st zone due to its distance (Fig. 19).

4.2 The three-terminal line faulted at 50 % of segment TS Dugo Selo – cable-overhead line

The three-terminal line faulted at 50 % of the segment TS Dugo Selo- cable-overhead line is 5 km, i.e. the distance to the T-point is 5.385 km. The distance between TS Resnik and the three-phase fault is 8.74 km. Furthermore, TS Mraclin is 24.1 km distant from the three-phase fault. The characteristic of R-X plot in TS Mraclin, i.e. ABB REL 511 relay, and the three-phase fault is at the distance of 24.1 km from the relay.

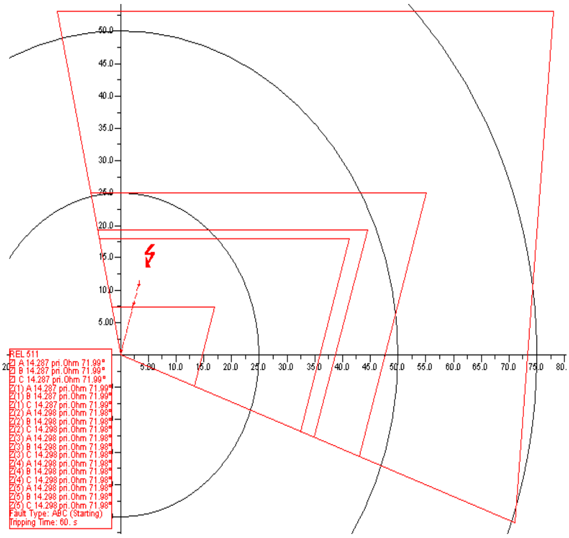

Fig. 20. REL511 relay in TS Mraclin

Characteristic of R-X plot in TS Resnik; Siemens 7SA511 relay; the three-phase fault is at the distance of 8.74 km from the relay.

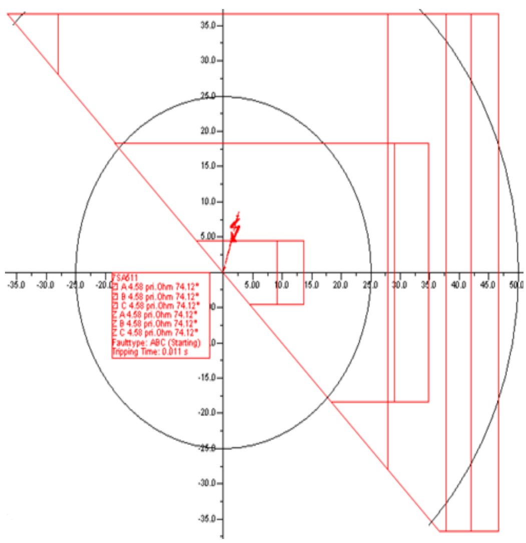

Fig. 21. 7SA511 relay in TS Resnik

Characteristic of R-X plot in TS Dugo Selo; Siemens 7SA6xx relay, the three-phase fault is at the distance of 5.385km from the relay.

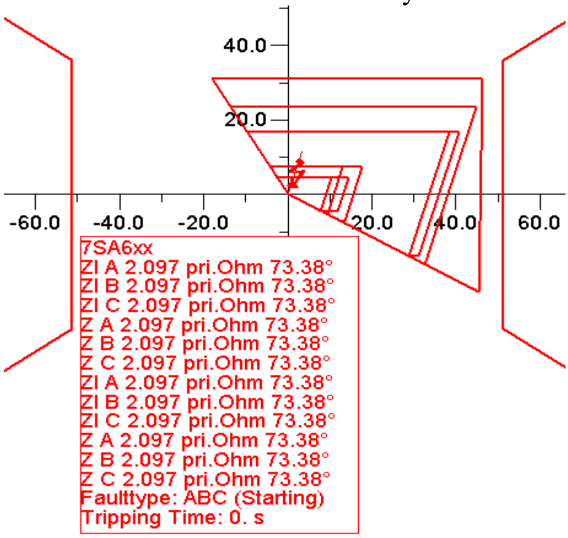

Fig. 22. 7SA6xx relay in TS Dugo Selo

The REL511 relay in TS Mraclin detects the fault in the 2nd zone due to its remoteness from the fault (Fig. 20). The 7SA511 relay detects the fault in the overlapping zone of the 1st and 2nd zone, but still in the 2nd zone (Fig. 21). The 7SA6xx relay placed in TS Dugo Selo detects the fault in the 1st zone due to its vicinity (Fig. 22).

5 CONCLUSION

Coordination and settings of digital relays can be checked and properly done by the *DIgSILENT PowerFactory* simulation software. Selectivity and coordination of a transmission network with a three-terminal line, protection of three-phase faults and single line to ground faults were performed on different sections and locations. The effects of infeed current and system parameter uncertainties in a distance relay on a three-terminal line have been discussed in this paper. A detailed fault analysis and extensive computer simulation of R-X impedance characteristic for different fault locations have been done.

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