Study of a phase-to-ground fault on a 400 kV overhead transmission line

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Abstract. Power utilities need to supply their consumers at high power quality level. Because the faults that occur on High-Voltage and Extra-High-Voltage transmission lines can cause serious damages in underlying transmission and distribution systems, it is important to examine each fault in detail. In this work we studied a phase-to-ground fault (on phase 1) of 400 kV overhead transmission line Mintia-Arad. Indactic® 650 fault analyzing system was used to record the history of the fault. Signals (analog and digital) recorded by Indactic® 650 were visualized and analyzed by Focus program. Summary of fault report allowed evaluation of behavior of control and protection equipment and determination of cause and location of the fault.

1. Introduction
At present, power quality is an area of growing interest in electric utilities, due to continuous increase of complexity and interconnectivity degree between power systems, as a result of electricity markets globalization, electricity being traded at national or regional level. All of these aspects require more and more complex operating conditions, related to system control and mutual support [1].

Power quality refers to following electromagnetic phenomena that characterize the voltage and current: transients, voltage dips, voltage swells, interruptions, voltage fluctuations, imbalance, waveform distortion and power frequency variations. These events differ in duration, harmonic spectrum and waveform magnitude, the most severe being voltage interruptions and dips, because industrial processes are very sensitive to these type of disturbances [2], [3].

Protection relaying is very closely related to power quality. In the presence of harmonic distortion and power frequency variations, protective relays can trip incorrectly. On the other hand, protective relaying fault clearing result in voltage sags, that affect power quality [4-8].

The faults that occur on High-Voltage (HV) and Extra-High-Voltage (EHV) transmission lines can cause serious problems in underlying transmission and distribution systems. This imposes severe conditions for protection and control systems, which must instant isolate the faults to maintain the system stability [1].

On HV and EHV transmission lines the majority of faults are typically single-phase-to-ground and transient (e.g., flashover across an insulator), being cleared using automatic reclosing. In this case, the line is disconnected in order to allow the arc to extinguish, and after the dead time, necessary to sufficiently deionize the arc path, the line can be reclosed to restore normal service [9].

Auto-reclosing can be used, also, to cleared the semi-permanent faults (e.g., a small tree branch falling on the line), but with a delayed action. If the fault persists after the first trip and closure, is used
double or triple-shot reclosing before the line will be put out of service [9]. Practice shows that the vast majority (almost 80%) of the faults are cleared after the first trip [1], [9]. 10% of the faults are cleared in the second reclosure, which is made after a time delay, 3% of the faults are cleared in the third reclosure and about 7% are permanent faults [9-11]. In the case of permanent fault, the reclosing relay is lockout, damaged part of the line being energized only after the fault has been removed.

2. Protections of 400 kV overhead transmission lines

In the case of 400 kV overhead transmission lines (OTL), basic protection against single-phase and poly-phase faults is provided at each terminal with two independent distance protections, which are of different construction types, completed with one communication channel to the opposite terminal, on separate paths [12], [13].

Each distance protection will send (simultaneously with the trigger signal for its own breaker), a signal through the communication channel, that will be received by the corresponding distance protection to perform one of the following functions: extending of zone 1 or accelerating of zone 2; fast triggering, with local control of the start and direction; in both cases, triggering will be selective on phases [13].

In the zone 1 extension method, zone 1 reach is normally set to cover 120% of line [14]. When fault occurs anywhere in the protected line, breakers at both terminals are tripped simultaneously without time delay and reclosed. Extending of zone 1 is done by means of the auto-reclosing relay under the following conditions:
- only for a certain type of short-circuit (typically only for single-phase short-circuits);
- only before or after the auto-reclose cycle (typically only before the auto-reclose cycle);
- coordinated with the auto-reclosing on the opposite terminal, for the fast clearing of short-circuits over the entire length of the protected line.

A contact of auto-reclosing relay is used to reset the zone 1 to 80% of line. If the fault is permanent, the breakers will be tripped according on the respective zone timers.

The major protections of analyzed 400 kV OTL are: line distance protection terminal REL 521 (group 1 of protections), distance protection relay LZ96a (group 2 of protections), auto-reclosing relay REXA 101 (group 2 of protections), distributed busbar protection REB 500 (group 1 of protections) and synchro-check relay SPAU 140 C.

2.1. Line distance protection terminal REL 521

REL 521 terminal has the following features [15]:
- fast and reliable fault detection, by simultaneous measurement of phase-to-phase and phase-to-earth loop impedances; numerical measuring elements are individual for each type of fault and each distance zones;
- minimum operating time is 13 ms;
- excellent possibilities for extensive combination of different options, based on multiprocessor design;
- numerical filtering and measuring technique ensures a correct performance during CT saturation and CVT transients;
- extensive self-supervision with fault diagnostics;
- detailed reports for the last ten disturbances (with up to 150 events for each disturbance).

Among the most important functions of REL 521 could be mentioned: distance protection (ZM); phase selection logic (PHS); power swing detection (PSD); power swing logic (PSL); pole slip protection (PSP); scheme communication logic for distance protection functions (ZCOM); current reversal and WEI logic for distance protection (ZCAL); automatic switch onto fault logic (SOTF); local acceleration logic (ZCLC); teleprotection; instantaneous overcurrent protection (IOC); time delayed overcurrent protection (TOC); thermal overload protection (THOL); stub protection (STUB); breaker failure protection (BFP); time delayed undervoltage (TUV) and time delayed overvoltage protection (TOV); disturbance report (DRP); disturbance recorder (DR); event recorder; fault locator
(FLOC); trip value recorder (TVR); autorecloser 1- and/or 3-phase, single or double circuit breakers [15].

REL521 terminal operates both for phase-to-phase and phase-to-earth fault, by distance protection function. It is possible single, two or three-phase tripping, through the separate phase selection function.

The distance protection zones can operate, independently of each other, in directional mode (forward - zones 1, 2, 4, or reverse - zone 3) or non-directional mode (zone 5). Distance protection zones 1, 2 and 3 can issue phase selective start and trip signals. Zone 5 can be used as a check zone, or as a time delayed zone, time delay being no more than 100 ms [15].

![Figure 1. Operating characteristic for one distance protection zone (forward direction) [15]](image-url)

Figure 1 presents the operating characteristic for one distance protection zone (in forward direction), where: Xph-e represents the reactive reach in the case of phase-to-ground (earth) faults; Xph-ph represents the reactive reach in the case of phase-to-phase faults; Rph-e represents the resistive reach in the case of phase-to-ground (earth) faults; Rph-ph represents the resistive reach in the case of phase-to-phase faults; Zline represents the line impedance [15].

Independent reactive reach setting for phase-to-phase and for phase-to-ground measurement secures high selectivity in networks. Simplified setting parameters reduce the complexity of necessary setting procedures.

2.2. Distance relay LZ96a

The distance relay type LZ96a is designed for the high-speed, selective protection of HV and EHV networks with effectively earthed neutral. LZ96a can be used to protect either overhead lines or cables, being ideal in networks with high short circuit power and critical stability conditions. It can detect all kinds of short circuit and offers important advantages: flexible and modular design, very short tripping time (20 ms) and very high accuracy [16].

The distance protection LZ96 uses the phase comparison principle for the measurement of the fault impedance. LZ96 has two measurement units with MHO characteristic. The first unit has three measurement zones. The first zone of this unit operates in permissive underreach trip transfer scheme and the second and third zones are for backup. The second unit has a measurement zone in permissive overreach trip transfer scheme that is used for the weak infed scheme too [17].

LZ96a relay has two starting units: a main starting unit that operates simultaneously with the measurement units, and an auxiliary starting unit which operates with the second measurement unit as a component of the weak infed scheme [16], [17].

The measurement principle also consider the system source impedance Zs, in order to detect ground faults of considerable impedance, where the characteristic inclines 14.4° approximately and expands towards the resistive axis [17].
2.3. Auto-reclosing relay REXA 101

REXA 101 auto-reclosing relay is used to restore the service of transmission lines when a circuit breaker is tripped single- or three-phase, due to a line fault [18].

The features of REXA 101 relay are: automatic high speed or delayed breaker reclosing; allows sequential reclosing of breakers in multibreaker arrangements; breaker position memory; the auto-reclosing function is performed by use of a pre-programmed single-chip microcomputer; allows extended shot 1 dead time when line protection communication link is out of service; prepared for coordination with synchronism and dead line check relay; reclaim time adjustable 10-180 s.

This relay allows setting three different time delays for dead time of the first single-phase reclosing, the first three-phase reclosing and the second three-phase reclosing [18]. Dead time settings are: single-phase, shot 1: 0.4-1.9 s (steps of 0.05 s); three-phase, shot 1: 0.25-60 s (steps of 0.05 to 1 s); three-phase, shot 2: 2-240 s (steps of 1 s) [18].

2.4. Distributed busbar protection REB 500

Distributed busbar protection REB 500 detects all bus and feeder faults for all type of system earthing. It operates selectively for all faults in the protected zone [19].

Among the main features of REB 500 could be mentioned: low-impedance busbar protection; stub and T-zone protection; high stability through fault, even in the case the current transformers are saturated; short tripping times; fully numerical signal processing; complete self-supervision; binary logic and timer in the bay unit; event recording; disturbance recording for power system currents [19].

Two independent measurement algorithms (stabilized differential current and directional current comparison) ensure a high functional reliability of REB 500, even in the case the busbar replica is not valid [19].

2.5. Bay control terminal REC 580

Bay control terminal REC 580 is used for the automation of complex HV substations [20]. REC 580 measures the instantaneous currents (I) and voltages (U) and computes the RMS values of U and I, active, reactive and apparent power (single and three-phase), energy values, power factor and frequency [20].

The most important functions of REC 580 are: control of circuit-breakers, isolators, earthing switches and fast earthing switches; switching between busbars; supervision of switchgear operating
times; interlocking between bays; single and/or three-phase multi-shot auto-reclosing; synchrocheck; voltage check [20]. Other features of REC 580 consist of: event recorder (with resolution of 1 ms); oscillation suppression; circuit-breaker operations counter; self-monitoring [20].

2.6. Synchro-check relay SPAU 140 C

Synchro-check relay SPAU 140 C is an integrated microprocessor-based voltage measuring relay designed to be used for checking the conditions for circuit breaker closing [21].

SPAU 140 C incorporates two identical stages (which operate as independent units), with two functions: synchro-check function and voltage-check function.

The synchronism is checked before the protections send the closing signal to the circuit breaker. Synchro-check function finds the instant when the voltages on both sides of the circuit breaker are in synchronism, i.e. the voltages have the same frequency, are in phase and with similar magnitude. When the frequency, phase angle and voltage conditions are fulfilled, the duration of the synchronizing conditions is checked so as to ensure that they will still be met when the contacts of the circuit breaker close. The delay between the moment when the closing signal is issued and the circuit breaker is closed is determined on the basis of the frequency and phase difference measured, being about 50-250 ms [21].

The voltage-check function checks the energizing direction, if one or both sides of the circuit breaker to be closed are dead [21].

2.7. Indactic® 650 fault analyzing system

The basic functions of a station (or substation) automation system are monitoring, control, recording and protection.

Before the occurrence of a fault in the protected area of analyzed OTL, the fault recorder device, Indactic® 650, capture all the information (both analogical and digital: voltages, currents, signaling, alarms, etc.) related to the fault and permits its reconstruction and analysis. Indactic® 650 has a compact structure, with integrated current and voltage transformers. It provides impedance-based fault locating with a precision of under ±2% in relation to the line length and has a complete independence from other equipment, such as protections. Moreover, Indactic® 650 allows the investigation of combined events [22].

Focus for Windows program allows the visualization and analysis of the signals (analog and digital) recorded by Indactic® 650. The phasor diagrams of voltages and currents, and their harmonic analysis can be achieved using Focus program, also [23].

Further is analyzed a phase-to-ground fault, on phase 1, of 400 kV OTL Mintia-Arad, in Mintia station.

3. Summary of the phase-to-ground fault report

3.1. Values of pre-fault signals

Time period allocated to record the pre-fault signals was 99.13 ms. In normal operation of analyzed OTL (Figure 3, t=-57 ms), the RMS values of phase voltages and phase currents are close.

The phase angle deviation between the voltages is approximately 120°; also, the phase angle deviation between the currents is approximately 120°.

It is noted a symmetric loading on the three phases of the analyzed overhead transmission line. The homopolar voltage and the homopolar current have low RMS values: U0=2.415 kV, I0=13.69 A.

At t=-16 ms (Figure 4), phase angle deviation of the currents are very different from the normal operation (the phase angle deviation between IL2 and IL1 is only 20°).

It is noticed the decrease of the voltage and a very high increase of the current, on phase 1 of analyzed OTL. The current on phase 3 decreases compared to normal operation. Homopolar voltage and homopolar current have a huge increase compared to normal operation (U0=329.5 kV, I0=3.88 kA). All this indicates the incipient stage of a phase-to-ground fault on phase 1.
3.2. Values of fault signals

In fault operation (Figure 5, t=4 ms), one can notice a significant increase of the homopolar quantities (U0=400.4 kV, I0=5.245 kA). Phase angle deviations of the currents are very different from the normal operation.
Figure 5. Marker 3: t=4 ms (fault). Phasor diagrams of voltages and currents

Figure 6. Analog signals recorded in the time period t=-99.24 ms...222 ms
At t=4 ms (Figure 5), voltage on phase 1 has a pronounced decrease and current has an even higher value than the previous moment. The impedance of OTL has decreased significantly from normal operation, which will cause the start of the distance protections.

Figure 6 and 7 show the analog and digital signals recorded in the time period t=-99.24 ms...222 ms (trigger at 16:20:07:769; number of samples: 1008; measuring time: 838 ms; marker 1: t=-57 ms, marker 2: t=-16 ms, marker 3: t=4 ms, marker 4: t=10 ms, marker 5: t=15 ms, marker 6: t=33 ms).

| Figure 7. Digital signals recorded in the time period t=-99.24 ms...280 ms |
|---------------------------------|
| **START L1 REL** 1 :1           |
| **START L2 REL** 0 :1           |
| **START L3 REL** 0 :1           |
| **GEN. START** 1 :1             |
| **GEN. TRIP R** 1 :1            |
| **DIST. TRIP** 1 :1             |
| **START L1 LZ** 0 :1            |
| **START L2 LZ** 0 :1            |
| **START L3 LZ** 0 :1            |
| **GEN. START** 1 :1             |
| **DIST. TRIP** 1 :1             |

At t=33 ms the faulted phase L1 was tripped. Figure 7 shows the start of distance protections:

- **START L1 REL** – start for group 1 of protections, through the line distance protection terminal REL 521, phase L1 (t=10 ms);
- **GEN. START REL** – general start of distance protection REL 521 (t=15 ms);
- **GEN. TRIP REL** – trigger pulse sent by distance protection REL 521 to the HV breaker of OTL, in Mintia station (t=15 ms);
- **DIST. TRIP REL** – trip of distance protection REL 521 (t=13 ms);
- **GEN. START LZ96a** – general start of digital relay LZ96a, group 2 of protections (t=2 ms);
- **DIST. TRIP LZ96a** – trip of digital relay LZ96a (t=4 ms).
Figure 8. Analog signals recorded in the time period t=99.29 ms...709 ms

Figure 9. Marker 3: t=133 ms (fault, after the reclosing of breakers). Phasor diagrams of voltages and currents
Figure 8 shows the analog signals recorded in the time period t=-99.29 ms...709 ms (trigger at 16:20:07:769; number of samples: 1008; measuring time: 838 ms; marker 1: t=9 ms, marker 2: t=115 ms, marker 3: t=133 ms, marker 4: t=145 ms, marker 5: t=150 ms, marker 6: t=183 ms, marker 7: t=368 ms).

At t=115 ms phase L1 was connected (reclosed). Because the fault persisted, at t=173 ms phase L1 tripped. Markers 6 and 7 show the three-phase tripping of OTL.

After the reclosing of breakers (Figure 9), one can notice a very high value of the current on phase L1 (IL1=5.374 kA). Also, homopolar quantities have very high values (U0=364.5 kV, I0=5.304 kA). The voltage is still low on phase L1 (UL1=63.84 kV). The fault was not removed. Because the defect persists, the protections will start again.

![Table]

| GEN. START | 1 :1 | 1  | 2  | 3  | 45 | 6  |
| DIST. TRIP | 1 :1 | 1  | 2  | 3  | 45 | 6  |
| E/F TRIP L2 | 0 :1 | 1  | 2  | 3  | 45 | 6  |
| AR ON REL/R | 0 :1 | 1  | 2  | 3  | 45 | 6  |
| START L1 RE | 1 :1 | 1  | 2  | 3  | 45 | 6  |
| START L2 RE | 0 :1 | 1  | 2  | 3  | 45 | 6  |
| START L3 RE | 0 :1 | 1  | 2  | 3  | 45 | 6  |
| GEN. START | 1 :1 | 1  | 2  | 3  | 45 | 6  |
| GEN. TRIP R | 1 :1 | 1  | 2  | 3  | 45 | 6  |
| DIST. TRIP | 1 :1 | 1  | 2  | 3  | 45 | 6  |

Figure 10. Digital signals record in the time period t=-99.29 ms...709 ms

Figure 10 shows the digital signals record in the time period t=-99.29 ms...709 ms (trigger at 16:20:08:769; number of samples: 972; measuring time: 808 ms; marker 1: t=9 ms, marker 2: t=115 ms, marker 3: t=133 ms, marker 4: t=145 ms, marker 5: t=150 ms).

When dead time (1 s) has elapsed, AR ON REL/REXA activates automatic reclosing, by sending reclosing signals to OTL breakers (in Mintia and Arad, by teleprotection). Auto-reclosing relay REXA requires a reclosing initiating signal from the line protection (REL 521). The breakers are reclosed when the reclose dead time delay has elapsed. Because the defect persists, the protections will start again, and OTL will three-phase tripped (markers 6 and 7).
Figure 11. Analog signals recorded in the time period $t=-98.29$ ms...334 ms (marker 1: $t=14$ ms, marker 2: $t=0$ ms, marker 3: $t=61$ ms, marker 4: $t=131$ ms)

3.3. Values of post-fault signals

![Phasor diagrams of voltages and currents](image)

Figure 12. Marker 4: $t=131$ ms. Phasor diagrams of voltages and currents
After the fault has been removed (Figure 12), it is noted a symmetric loading on the three phases of the analyzed overhead transmission line. The homopolar voltage and the homopolar current have low RMS values: \( U_0 = 10.77 \text{kV} \), \( I_0 = 17.56 \text{A} \). At \( t = 131 \) (Figure 11, marker 4) analyzed OTL is in normal operation.

Focus program allows the harmonic analysis of the voltages and currents up to 10-th order. Figure 13 (marker 4: \( t=131 \text{ ms} \)) shows the harmonic spectra of phase voltages and currents.

![Harmonic spectra of phase voltages and currents](image)

| Phase | THD UL | THD IL |
|-------|--------|--------|
| L1    | 3.88%  | 21.92% |
| L2    | 4.19%  | 25.06% |
| L3    | 5.16%  | 30.65% |

*Figure 13. Marker 4: \( t=131 \text{ ms} \). Harmonic spectra of phase voltages and currents*

4. Conclusions

Fast clearing of EHV faults is essential to maintain power quality in an area, because events on the EHV system affect the underlying transmission and distribution systems.

The cause and location of the fault can quickly be determined by analyzing the summary of the fault report, and the behavior of the associated control and protection equipment can be evaluated.

Are noticed especially the facilities offered by Focus program in analyzing of analog and digital quantities; the visualization of RMS values, phasor diagrams and harmonic analysis are in real time.

Fault analysis allows the improvement of protective designs and switching strategies, so that future faults will be prevented.

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