High Voltage Power Line Transient Fault Analyzing and Modelling

Marius Fișcă*, Mihail Abrudean*, Vlad Mureșan*, Mihaela Ungureșan**

** Automation Department, Technical University of Cluj-Napoca, 28 Memorandumului Street, 400114 Cluj-Napoca, Romania (e-mail: mariusfisca@gmail.com, mihai.abrudean@aut.utcluj.ro, vlad.muresan@aut.utcluj.ro)*
*** Physics and Chemistry Department, Technical University of Cluj-Napoca, 28 Memorandumului Street, 400114 Cluj-Napoca, Romania (e-mail: mihaela.unguresan@chem.utcluj.ro)*
Correspondence: mihaela.unguresan@chem.utcluj.ro

Abstract: The research presents a protective control structure for fast and reliable high voltage power line protection that focuses on network parameters that respond to transient faults conditions, starting from the analysis of a real event. In case of overhead power lines, approximately 80% of the total registered faults have a transient character. Therefore, the management of transient faults is important because this have a direct impact on the energy distribution process and have a large influence on the quality of energy supplied to consumers. The development of mathematical models of wide applicability, to accurately represent the propagation of a transient fault on the 110 kV lines is possible through data analysis recorded during real life events, which constitute a clear representation in time of an actual fault. The use of these mathematical models made it possible to reduce the detection time of transient faults, ensuring benefits in terms of reducing the extent of power outages, which leads to shorter recovery times. The proposed operating algorithm of the developed control structure for transient fault detection and line protection triggering allows the improvement of distance protection reaction in the event of a transient fault, to safely overcome critical moments in network operation, aspects that recommend the proposed solution for practical implementation.

Keywords: modelling, simulation, fault control structure, high voltage power lines, power line fault, transient fault, power lineprotection system, experimental results.

1. INTRODUCTION

Power distribution lines are the link between power sources, urban centers and industrial areas. Protecting these power paths through automatic devices is essential in order to maintain continuity in power supply.

In practice, the phenomenon of air insulation penetration, in case of a transient fault, is preceded by a predischarge, which ionizes air at the fault location and creates a path for arcing which triggers an avalanche of electrons moving towards the ground generating a conduction current, while the electrical discharge in case a persistent fault usually occurs violently due to electrical insulation failure, or mechanical failure of the power line structure, depending on the nature of the fault. These characteristics make it possible to identify the fault from the early stages creating the possibility of sensitization protections for a slightly improved response time, avoiding additional damage to the electricity distribution network.

In case of a transient fault, caused by the accidental contact between a forign object and the active parts of the line, such as vegetation in the corridor of the power line, it is possible to resume the power supply with the help of the Auto-Reclose automation, after extinguishing the electric arc as a result of fault clearing, while in case of a persistent fault a physical intervention is needed to repair the network. Therefore, this manuscript focuses on handling transient faults and restoring power to the faulted line as quickly as possible.

The aim is to determine the mathematical models that accurately reproduce the dynamics of the experimental response of the energy distribution process in front of a transient fault, ensuring high accuracy in fault detection and clearing.

In order to do so comparative analysis between real life events and mathematically simulated responses is required.

Other mathematical models proposed in the technical literature for power line fault modeling are nonlinear models (Doria-García et al., 2021; Ferraz et al., 2016) witch use a high impedance fault model, to replicate the behavior of currents and can be used with accuracy only for high intensity currents, according to the presented methods. These types of models are used primarily to estimate the fault location in transmission lines and are not suitable for rapid detection.

On the other hand, the techniques described in previous works (Tarko et al., 2021) do not target the particularities of the transiet fault and do not include details on fault behaiviure, only analysis is carried out for highvoltage power line single-phase faults to the tower structures, without targeting the general character of the faults and their implications on the energy distribution process.

The main advantage achieved by the proposed work is that transient faults are less felt through out the distribution network and are prevented from becoming persistent faults.

2. EXPERIMENTAL DATA

Distance protection is the main protection of 110 kV lines against single-phase and polyphase faults. The distance protection processes current and voltage samples provided by the data acquisition process of the digital protection relay, as equivalents to the analog process quantities. The analog quantities obtained in the secondaries of the current and voltage transformers are taken at discrete moments of time, at intervals of 1 ms, as a sampling step. A single sample/millisecond is obtained for each individual analog input. In the data acquisition process, the samples obtained with a sampling frequency of 1000 Hz, representing a number of 20 points/period, are digitally filtered. An efficient rejection of the disturbances that can appear on the analog channels is ensured, thus obtaining immunity to noises and all higher harmonics of the currents and voltages are rejected. To precisely determine the experimental response of the propagation of a single-phase earth fault, all these have to be taken into account (Celin, 2015).

The case study was carried out for a 110 kV Overhead Power Line (OPL) in the event of transient fault, on phase R, triggered by Distance Protection, cleared by Automatic reclosing AR(+). Analyzing the event stored in the memory of the digital protection relay, we had access to the line's operating parameters before the registration of the fault, to fault recorded values and to the protection operation mode, as a reaction to the fault.

The oscillogram of the event is shown in Fig. 1.

From the analysis of the event it follows that at time t= –150 ms, 150 ms before the occurrence of the fault, the 110 kV OPL was in operation, under load and provided system interconnection with consumers ensuring the energy supply. Phase currents and voltages are balanced while the line is in normal operating mode and their registered values are those listed in the table, corresponding to the –150 ms time. Knowing the transformation ratio of the current transformer N_{CT}= 600/5 A and the transformation ratio of the voltage transformer N_{VT} = 110/0.1 kV, in service for the analysed power line, as rated primary and secondary measurement transformers functional values, the primary currents (I) and voltages (V) corresponding to the secondary ones, recorded on each phase, are computed, their results are as follows:

I_R= 112.2 A; I_S= 102.7 A; I_T= 106.7 A;

V_R= 69.0kV; V_S= 69.1kV; V_T= 69.5 kV;

By multiplying the phase voltages by the root of 3 results in approximately 119 kV for the line voltages, this being a normal service voltage for a 110 kV OPL (Rusu et al., 2009).

At the time of the appearance of the fault, t= 0 ms, a huge increase in the recorded R-phase electric current (IR), can be observedand a sharp drop in voltage on the defective phase (UR) is registered at the same time. The healthy phases S and T also register an increase in currents and a slight change in voltages. The recorded values are listed in the oscillogram table at t= 0 ms.

The primary current of the faulted phase, proportional to the secondary IR, now reaches the value of 1248 A, recording an 11-fold increase, which endangers the constructive structure of the 110 kV power line. Also at the time t= 0 ms, when the fault starts to manifest itself a sudden drop in voltage magnitude on the faulted phase is recorded, this reaching a mere 12.20 kV (line primary voltage) (Belčević et al., 2022). Consequently, the experimental results for the transient fault are included in Table 1.

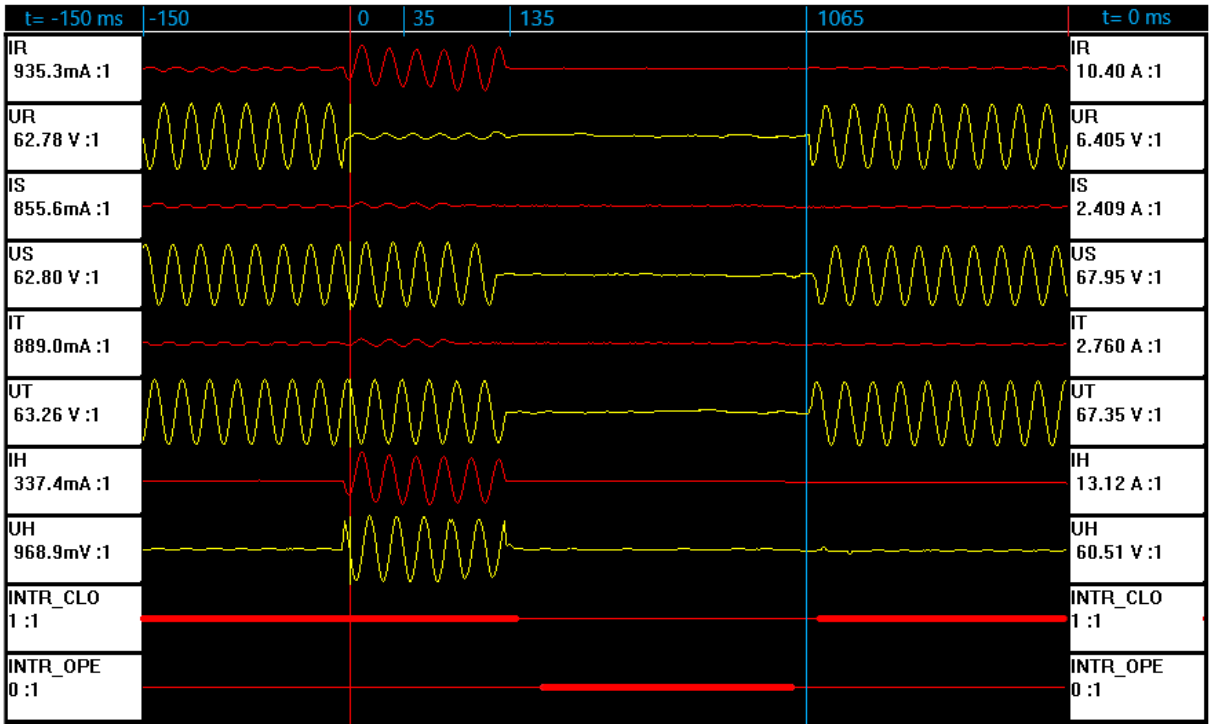

Fig. 1. Oscillogram of a transient fault reported on the 110 kV power line.

The cause is a single-phase to ground short circuit on phase R, which determines the start-up of the distance protection. At the moment t= 135 ms, the power line is disconnected, the time being necessary for the activation of the distance protection and the effective disconnection done by the 110 kV circuit breaker. The disappearance of the fault current and voltage, but also of the normal voltages, is noted, the line is now in a disconnected state, without voltage, as a result of the operation of the distance protection from the power station. When a transient fault occurs on a distribution line, it is very important to detect the fault as quickly as possible so as to restore power as soon as possible. When the protection is actuated, the trigger pulse also activates the Auto-Reclose device (AR automation). After the AR pause has passed, in the present case set to 0.8 seconds, the AR automation transmits a reclosing impulse to the circuit breaker, and since the fault is transient, energy supply is restored on the 110 kV OPL in 1.065 seconds from the moment the fault was initially reported. The electric arc at the point where the fault is incident is extinguished during the AR pause by deionization of the fault-arc path. The purpose of the distance protection is to protect the high voltage power line and associated equipment from damage due to overcurrent in the event of a fault along that line. To do so and also to ensure selectivity, the distance protection acts in time steps, protecting specific zones (De Aguiaret al., 2018). Regarding the studied transient fault it is best that the distance protection reacts in the first step, which corresponds to protection Zone1, covering 80% of the line length and triggering without timing in the interest of restoring power to consumers as quickly and efficiently as possible (De Jesús Jaramillo Serna et al., 2019).

Checking the operation of the protection can be done by referring to the system data, according to the protection plan approved by the distribution network operator. The level of threshold voltages for each protection step can be obtained from calculations, depending on the primary impedances established by the protection plan. The indications of the oscillogram, when displaing the line parameters of the event is done in secondary values of currents and voltage, therefor to obtain the voltage level required for checking the protection it is necessary to calculate the secondary impedance Z_{1sec}, using the equation:

$$Z_{1sec}=\frac{N_{CT}}{N_{VT}}\cdot Z_1=\frac{120}{1100}\cdot 8=0.872\ \Omega \qquad (1)$$

where $Z_1$is the established impedance for Zone 1.

Checking of the operation in the correct step of the protection, can be done according to the short-circuit current registered as a single-phase fault (related to the short-circuit impedance Z_{shc}) according to those illustrated in Fig. 2:

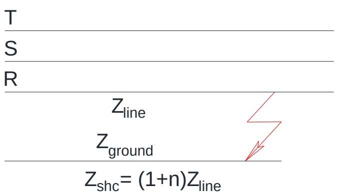

Fig. 2. Specificity of single-phase faults.

For the situation in question, the voltage level for the protection actuation Zone 1 is determined using the equation:

$$V_1=Z_{1sec}\cdot I_R\cdot(1+n)=0.872\cdot 10.4\cdot(1+0.8)=16.32\ V \qquad (2)$$

where I_R is the short-circuit current recorded at the time of the fault and n is the ground factor of the line, which takes values between 0.6 and 1 depending on the specifics of the area crossed by the line (Vulcu, 2007).

In case of the analyzed fault, the distance protection worked correctly in Zone 1, the voltage at the time of the fault being 6.405 V, in the shortest time possible considering the standard operation of the distance protection.

Table 1. Experimental results - measurement samples.

Time	Transient fault			
(ms)	I_R current R phase (A)	V_R voltage R phase (V)	Primary Current CT (A)	Primary Voltage VT (kV)
-20	2,966	55,14	355,92	105,06
-19	3,494	55,12	419,28	105,02
-18	3,760	54,59	451,20	104,01
-17	3,814	53,10	457,68	101,17
-16	3,815	50,31	457,80	95,85
-15	3,946	46,35	473,52	88,31
-14	4,417	41,85	530,04	79,73
-13	5,209	37,42	625,08	71,29
-12	6,168	34,07	740,16	64,91
-11	7,196	32,31	863,52	61,56
-10	8,095	31,87	971,40	60,72
-9	8,802	31,87	1056,24	60,72
-8	9,247	31,08	1109,64	59,23
-7	9,466	28,61	1135,92	54,51
-6	9,529	23,36	1143,48	44,51
-5	9,529	13,57	1143,48	25,85
-4	9,579	7,322	1149,48	13,95
-3	9,725	6,314	1167,0	12,03
-2	9,938	6,359	1192,56	12,12
-1	10,20	6,403	1224,0	12,20
0	10,40	6,405	1248,0	12,20
1	10,57	6,406	1268,4	12,21
2	10,68	6,404	1281,6	12,20
3	10,74	6,404	1288,8	12,20
4	10,75	6,300	1290,0	12,00
5	10,72	6,193	1286,4	11,80
6	10,65	6,069	1278,0	11,56
7	10,54	5,956	1264,8	11,35
8	10,41	5,858	1249,2	11,16
9	10,22	5,760	1226,4	10,97
10	10,04	5,684	1204,8	10,83
11	9,847	5,634	1181,64	10,73
12	9,678	5,623	1161,36	10,71
13	9,570	5,630	1148,4	10,73
14	9,519	5,659	1142,28	10,78
15	9,433	5,670	1131,96	10,80
16	9,470	5,632	1136,4	10,73
17	9,463	5,578	1135,56	10,63
18	9,418	5,546	1130,16	10,57
19	9,388	5,451	1126,56	10,39
20	9,335	5,437	1120,2	10,36

3. MATHEMATICAL MODELS FOR THE DETERMINATION OF EXPERIMENTAL VOLTAGE AND CURRENT RESPONSES

The time interval considered, from the event analysis, is from −20 ms to 20 ms. This time interval of 40 ms is the most relevant in terms of fault propagation, as it captures the operation of the high voltage power line before the occurrence of the fault by 20 ms, the occurrence of the fault with the protection start-up at 0 ms and 20 ms of the evolution of the fault. Fig. 3 presents the experimental response - the evolution of the V_R voltage during the 40 ms selected interval. The R-phase voltage of the analyzed event is sampled using the step of 1 ms and captures the occurrence of the fault that causes the tripping of the high voltage line, as previously described, by the distance protection.

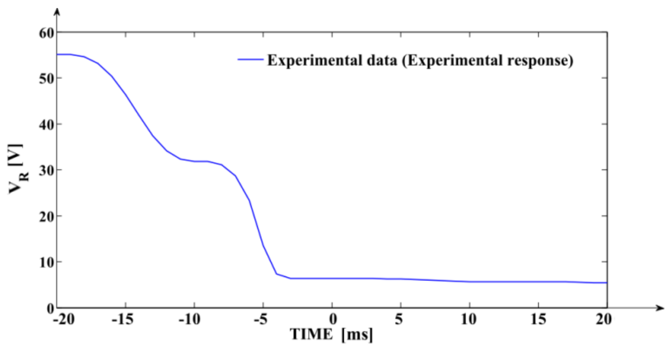

Fig. 3. Experimental response V_R voltage.

The tripping of the 110 kV line is generated, in this case, by a single-phase to groundtransient fault, which causes a sharp drop in voltage on phase R. To determine the mathematical model that best describes fault propagation, approximation based on the experimental response is rerquired. First, using Matlab's real case emulation properties, the process proportionality constant and the process time constants needed to develop the mathematical models describing the fault, were determined using approximations. In order to find the necessary information to obtain the derivative of the $V_R(t)$ signal for the specified time interval, it is necessary to mathematically model the fault propagation phenomenon (Mureșan et al., 2022).

The mathematical model developed for this single-phase short-circuit can be expressed by a third-order transfer function, of the following forme:

$$H(s)=\frac{K}{(T\cdot s+1)^3} \tag{3}$$

with T representing the time constant of the fault evolution and K the proportionality constant.

The proposed transfer function is simulated as a unit-step type input signal and the obtained response is subtracted from the initial value of the V_R voltage before the appearance of the fault. Both constants T and K were determined using an iterative procedure (Fișcă et al., 2023) that approximates the experimental response with that of the proposed mathematical model, aiming to minimise the mean square error as a quality indicator between them, thus the transfer function takes the form:

$$H(s)=\frac{-49.703}{(3.75\cdot s+1)^3} \tag{4}$$

The third-order identified model demonstrates high precision, due to the fact that it has been refined by taking into consideration several possible time constantvalues for the evolution process, in order to determine the most likely response.

The fault propagation process can also be simulated by using Gaussian models. The Gaussian function, that indicates the signal dynamics during fault evolution, is:

$$x_G(t)=x_i+K\cdot\left(1-e^{-\frac{t^2}{T^2}}\right) \tag{5}$$

where T represents the time constant for the fault evolution process, $x_G(t)$ represents the generated $V_R(t)$ signal of the Gaussian model and x_i is the initial value of the response.

As before, an iterative procedure was needed to find the T time constant of the fault evolution process so that the developed mathematical model, represented by the following relation, has the highest accuracy:

$$x_G(t)=55.14-49.703\cdot\left(1-e^{-\frac{t^2}{140}}\right) \tag{6}$$

The similarities of the two different proposed mathematical models responses via precision of simulation of the experimental response is shown by the following graph, Fig. 4.

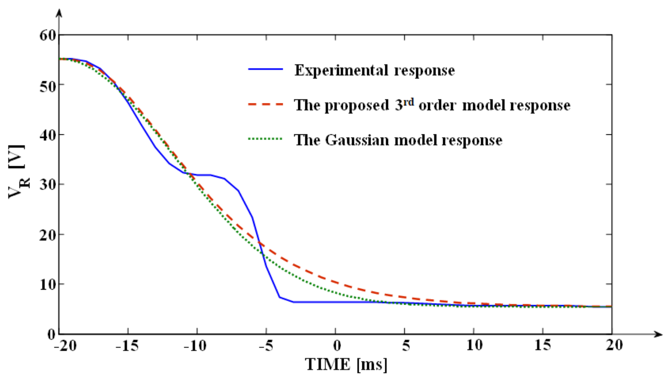

Fig. 4. Similarities of the proposed mathematical models.

Fig. 4 shows that both types of proposed mathematical models have a high validity, their generated responses accurately follow the dynamics of the voltage response. Consequently, the use of both types of proposed mathematical models for various applications, among which the application presented in this paper is viable.

Fig. 5 shows the OPL operating modes and the evolution phenomenon of the fault represented by the dynamics of the $V_R(t)$ voltage. The response is obtained by using the effective values of the R-phase voltage generated by simulating the proposed third-order mathematical model. This simulation proves the validity of the mathematical model because the generated waveforms are similar to the real ones presented in the process.

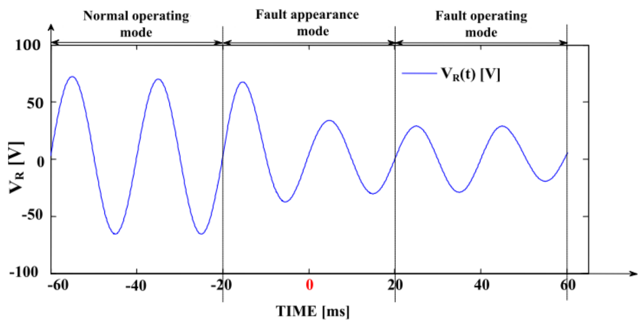

Fig. 5. Appearance of the fault.

For high accuracy it is necessary to mathematically model the intensity of the R-phase electric current, the distance protection being a complex protection that uses both voltage and current. The experimentally obtained $I_R(t)$ signal follows the dynamics shown in Fig. 6.

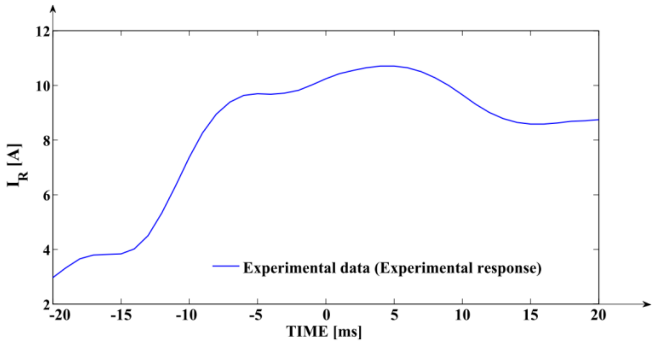

Fig. 6. Experimental response I_R current.

The experimental response resulting from Fig. 6 indicates that the dynamics of the $I_R(t)$ current in failure mode could present overshoot. As a consequence the representation of the dynamic of the $I_R(t)$ current must be performed using a second-order transfer function witch takes this fact into aqount:

$$H(s)=\frac{\omega_n^2}{s^2+2\cdot\ni\cdot\omega_n\cdot s+\omega_n^2} \tag{7}$$

where $\ni$ is the damping factor, and ω_n is the natural pulsation of the amortized process.

To determine the factors that make up the transfer function the following experimental values are required:

- the I_R value at −20 ms as the initial experimental response value: x_0= 2.966 A;
- the maximum I_R of the experimental response value during this 40 ms interval: x_{max}= 10.75 A;
- the steady state experimental responsevalue: x_{st}= 9.38 A.

With the help of these acquired values, the overshoot σ of the R-phase current is calculated, using the following analytical expression:

$$\sigma=\frac{(x_{max}-x_0)-(x_{st}-x_0)}{x_{st}-x_0}=0.214 \tag{8}$$

It thus results that the overshoot expressed as a percentage value is 21.4%. Knowing the amount of overshoot, the damping factor can be obtained using the relationship:

$$\ni=\sqrt{\frac{\ln(\sigma)^2}{\pi^2+\ln(\sigma)^2}}=0.698 \tag{9}$$

By analyzing the oscillogram data, it follows that the fault manifests itself over a period of approximately 135 ms, but the current fluctuates the most over a period of 40 ms, so the considered response time of the $I_R(t)$ signal during fault progress is t_{shc}=40 ms. Thus, the natural pulsation can be computed using the following expression:

$$\omega_n=\frac{4}{\ni\cdot t_{shc}}=0.14\ {}^{1}/_{ms} \tag{10}$$

The mathematical model that traces the evolution of the fault current can be described using the initial transfer function, as follows:

$$H(s)=\frac{0.0196}{s^2+0.195\cdot s+0.0196} \tag{11}$$

Fig. 7 presents the proposed response determined with the help of the second-order mathematical model in comparison with the experimental response of the process. The validity of the proposed mathematical model is noted, due to the fact that the dynamics of its response accurately traces the dynamics of the experimental response.

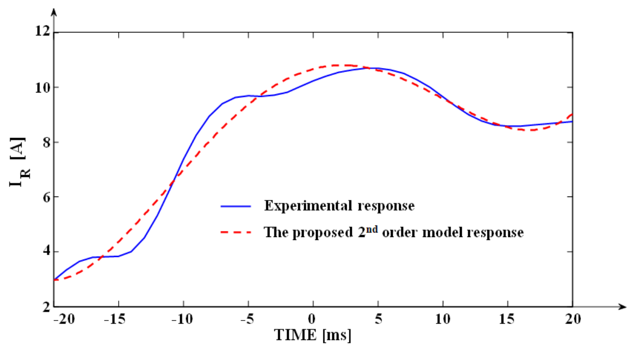

Fig. 7. Second-order mathematical model response compared to the experimental response.

Fig. 8 shows the dynamics of the $I_R(t)$ current generated with the help of the proposed mathematical model. The dynamics of the current response reveals the validity of the mathematical model by the fact that the generated waveform is similar to the real one in the process, presented in the previous section.

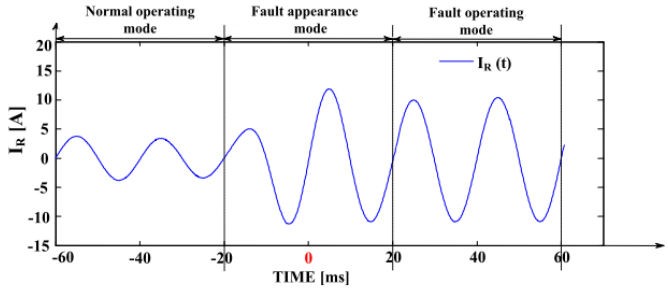

Fig. 8. Appearance of the fault.

The fault appearance phenomenon is visible in the range of [−20; 20] ms. The overshoot is visible at the second positive pulse in the length of time between [−20; 20] ms, this having the amplitude greater than that of the positive pulsations in a period of time between [20; 60] ms.

4. PROPOSED STRUCTURE FOR TRANSIENT FAULT DETECTION AND LINE PROTECTION TRIGGERING

Based on mathematical modeling of the voltage and current evolution during the occurrence of a fault, previously determined, an original structure is proposed for fast identification of a transient fault and line circuit breaker tripping with the purpose of reducing consumer downtime. Energizing the line, after the transient fault has been accurately identified and rapidly triggered with the help of the proposed structure, is the responsibility of the Auto-Reclose automation (AR) that works together with the distance protection. The proposed automatic control structure for transient fault detection and line protection triggering is presented in Fig. 9.

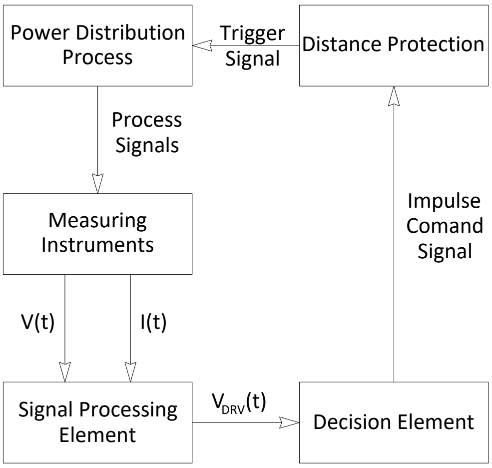

Fig. 9. Automatic control structure for transient fault detection and line protection triggering.

In Fig. 9 the high voltage power line considered as the case study of this analysis, involved in the electricity distribution process is referred as Power Distribution Process. Measuring instruments stands for voltage and current transformers responsible for acquiring the process signals - the voltage $V_R(t)$ and $I_R(t)$ current.

The Signal Processing Element is used to generate the $V_{DRV}(t)$ signal, a voltage derivate in relation to time involved in the decision making, within the Decision Element, of whether or not the monitored event represents a fault.

Both signals $V_R(t)$ and $I_R(t)$, mathematically modeled in the previous section, are needed to develop a fast fault detection algorithm. For powering up the algorithm of the proposed automatic control structure, $V_R(t)$ represents the fundamental signal and the $I_R(t)$ signal represents the support signal in the fast fault detection procedure. The two signals vary strongly in fault appearance mode, namely V_R signal shows a strong monotonic decline until it stabilizes in fault operating mode, and the I_R signal shows a strong and monotonic increase until it stabilizes, as well in fault mode (Radojević, 2007).

The operating algorithm of the presented structure involves the following stages, for fast detection and tripping the line through protection, in case of detected failure:

- the effective working value of the $V_R(t)$ voltage and $I_R(t)$ current have to be set, according to the power line characteristics;
- the time derivative of the $V_R(t)$ signal is calculated;
- the minimum values that the derivatives assume at a specific istant time of the $V_R(t)$ signal are determined for several relevant values, in case of failure, obtained from operating experience and experimental data;
- the arithmetic mean of the minima of the derivatives is calculated in order to establish an average voltage reference threshold in the event of a fault, marked as V_{med};
- the $V_{DRV}(t)$ is calculated as the derivative of the $V_R(t)$ signal and its minimum value is determined if conditions for the early manifestation of a fault are met, namely two consecutive decreases in value of the recorded voltage at the same time with two consecutive rises in value of the recorded current;
- the minimum value of $V_{DRV}(t)$ is compared with the average value of the reference derivatives V_{med} to detect a fault.

Once the time derivative of the voltage signal is calculated, its minimum value is recorded and the average voltage reference is established, the online monitoring of voltage and current can begin as a full time process. If two consecutive drops in voltage value are registered at the same time of two consecutive increases in current instantaneous value the derivative of the phase voltage signal, $V_R(t)$ related to time, is calculated and its minimum value, related with the moment the derivative changes monotony, is compared with the voltage previously determined reference. If the value of the $V_{DRV}(t)$ falls beneath the established reference the occurrence of a fault is detected.

In case of the event presented in this manuscript the first-order derivative of the phase voltage signal related to time is generated using the Gaussian mathematical model and the following relation:

$$V_{DRV}(t)\approx\frac{1}{T_h}\cdot[V_R(t+T_h)-V_R(t)] \tag{12}$$

where $V_{DRV}(t)$ represents the time derivate of the phase voltage signal, at a certain time t of the power distribution process and T_h represents the approximation step of the derivativeof 1 ms (the same as the process sample step).

The dynamics of the $V_{DRV}(t)$ signal with respect to time, is shown in Fig. 10, for the case of the documented transient fault.

Detection is performed for both voltage and current by subtracting the instantaneous values of the signals from the previously recorded values, at each sampling step. Because the conditions regarding the decrease in voltage and increase in current values were fulfilled at the same time, we passed to the next stage of determining the the first-order derivative of the voltage signal as shown in Fig. 10. The minimum value of the derivate with respect to time of the $V_R(t)$ signal is $V_1= -3.6031$ V/s, identified at $t_1= 8.4$ ms. According to (Fișcă et al., 2023), the presented experimental data and the minimum V_1 value shown above, the V_{med} reference voltage is set at $½\cdot V_1= -1.8015$ V/s.

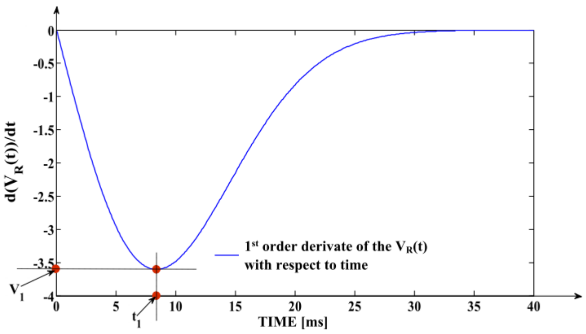

Fig. 10. Dynamics of the first-order derivative of the $V_R(t)$ signal.

The operating logic of the automatic control structure for transient fault detection and line protection triggering is presented in Fig. 11.

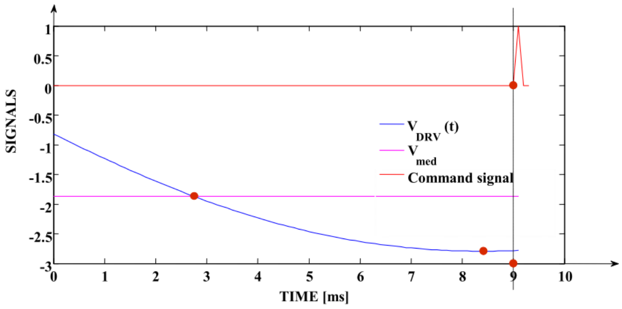

Fig. 11. Function logic of the automatic control structure for transient fault detection and line protection triggering.

Moment 0 on the time axis represents the moment when a possible fault is first reported, and the structure starts to calculate the $V_{DRV}(t)$ derivative. This step takes place after 2 milliseconds from the start of the detection corresponding with two unexpected voltage decreases together with two increases in current.

The left red dot in Fig. 11 represents the moment in which the $V_{DRV}(t)$ signal falls beneath the established reference V_{med}. The right red dot, located in the 8-9 ms time interval highlightes the moment when the $V_{DRV}(t)$ signal reaches the minimum point and the change in its monotony is recorded. In consequence, the event taking place is classified as a fault, and at 9 ms the comand signal is generated, witch in turn triggers the signal for tripping the 110 kV line circuit breaker through the Distance Protection. The command signal is marked as a spike impulse highlighted with the red vertical, represented as logical value.

In order to prevent false tripping and to improve protection selectivity, both conditions highlighted in Fig. 11 through the red dots must be satisfied to generate the line trigger signal. These conditions assume that not only the $V_{DRV}(t)$ signal reaches a minimum point and changes its monotony but also needs to fall below the imposed reference voltage. Thus, even if the monotony change takes place, without the derivative signal falling below the imposed threshold, the event is not classified as a fault, but as a temporary disturbance witch has little effect on the energy distribution process.

The rapid detection of the fault refers to the reduction of its identification time. Analyzing the proposed mathematical models, the appearance time of the minimum derivative of the $V_R(t)$ signal in relation to time is 8.4 ms, identified in Fig. 10. In this context, using the derivative approximation step T_h= 1 ms, this time as the operation step of the automatic control structure for transient fault detection and line protection triggering, the highest probability is that a reaction of the protection system to appear after 9 ms from the identification of the fault.

From Fig. 11 it results that the proposed structure reacts to the appearance of a fault in the considered time interval [−20; 20 ms], after 11 ms. These elapsed time of 11 ms is composed of 2 ms in witch the fault starst to manifest itself and change detection of the $V_R(t)$ and $I_R(t)$ occurs and another 9 ms elapsed time due to the identification of the $V_{DRV}(t)$ signal monotony change and emission of the command signal. Therefore the reaction of the distance protection is enhanced in front of a transient fault with 9 ms, when the proposed structure activates a fault clearing procedure.

The proposed control structure from Fig. 9 was implemented and simulated in MATLAB/ Simulink. Simulations results show that a transient fault will be identified after 11ms from its initial appearance, it will be reported as a fault 9 ms earlier and then it will be cleared by the Auto Reclosing of the power line, also 9 ms earlier. In conclusion, the greatest probability is that the proposed solution will identify a transient fault 9 ms from its initial moment, when it is in its early stage, depending on the exact moment of the monotony change of the monitored signal, always correlated with the extent of the fault. The high performance achieved in selectivity and sensitivity by the proposed detection solution creates the possibility of hy speed operation of the distance protection, which in turn offers the advantage of avoiding significant damage to the power line and to the related distribution network. It also creates the possibility of a quick restoration of the power supply, therefore the impact that transient faults have on the distribution process and on consumer supply is much diminished.

5. CONCLUSIONS

The manuscript introduces a new type of automation which aims to help detect a transient fault and after that to establish a quick restoration of the power line.

The performance of the automatic control structure for transient fault detection and line protection triggeringis successfully tested through mathematical modeling. In addition to the development of the control structure, the manuscript analizes the interesting phenomenon of power line function when confronted with a transient fault. The proposed mathematical models were developed based on a real event and generate high accuracy responses in terms of voltage and current. Due to the high precision generated by the proposed mathematical models high-speed transmission line protection can be achived while minimizing network disturbance, ensuring reduced Auto-Reclose operation time.

Results obtained in the simulation of the automatic control structure proposed for the detection of transient faults and the triggering of line protection show the benefits of its use in the event of the occurrence of a transient fault, namely the exposure time of installations to high short-circuit currents and the effects of the fault are drastically reduced, by increasing the reaction speed of the distance protection together with its selectivity, damage to power lines at the fault site is thus avoided, the circuit breakers of the line, which must interrupt the high fault currents, are better protected, and dangerous deforming regimes are avoided in neighbouring installations with positive effects on the electricity distribution process.

The transition from the normal operating mode of the power line to the stabilized single-phase ground fault regime, refered to as the fault operating mode is made through a transient process and includes the following phenomena that take place consecutively, namely:

- Discharging the capacity of the faulty phase and additionally charging the capacity of the healthy phases, in which case the discharge current of the faulty phase, respectively the charging currents of the healthy phases have the same direction;
- The short-circuit current generated by the fault has a high value, causes an increase in the voltage drop in all the impedances it passes through, thus contributing to a decrease in network voltage with negative effects on the supply of consumers.

The much-improved response time of the distance protection ensures the stability of the power system, partialy avoiding the above phenomena, plus avoiding additional interruptions of the power distribution process, due to fault spreading, in general, and because of high short-circuit currents and overvoltages on healthy phases, in particular.

The proposed solution for rapid fault detection meets all the important requirements needed for a high-performance automatic protection system, namely: safety in operation, speed, selectivity and sensitivity.

The new automatic protection systems, currently present in power distribution facilities, allow the implementation of operating models, in programming language, without involving high costs and structural changes. Intervention in the working program of digital terminals is possible through dedicated software, with the possibility of obtaining immediate results.

Practical software solutions for implementing the operating algorithm of the transient fault detection and line protection triggering should cover and ensure several skills of service in order to fulfil its main objectives. The main inputs that expose the important features of the proposed structure, that must be taken into account when developing the necessary software, are presented below:

- Collect information. Ensures accurate collection of network data when a fault occurs. This information is composed by the status of the power line and also of the fault values.
- Protection start-up. Along with data collection from the system it is necessary to execute the algorithm, in order to detect the fault and tripp the power line.
- Results. Fault detection should be carried out together with the distance protection program that triggers the fault considering various important factors from the system, so power is restored as quickly as possible.

REFERENCES

Belčević, N. and Stojanović, Z. (2022). Using voltage signals for transient fault detection on overhead lines. *International Journal of Electrical Power & Energy Systems*, (137), pp. 212-329.

Celin, M. (2015). *Earth fault current distribution on transmission networks*, Università degli Studi di Padova, Padova, Italy, pp. 5-76.

De Jesús Jaramillo Serna, J. and López-Lezama, J. (2019). Calculation of Distance Protection Settings in Mutually Coupled Transmission Lines: A Comparative Analysis. *MDPI Energies*, (12), pp. 1-35.

De Aguiar, R., Dalcastagnê, A., Zürn, H., Seara, R.(2018). Impedance-based fault location methods: Sensitivity analysis and performance improvement. *Electric Power Systems Research*, (155), pp. 236-245.

Doria-García, J., Orozco-Henao, C., Leborgne, R., Danilo Montoya, O., and Gil-González, W. (2021). High impedance fault modeling and location for transmission line. *Electric Power Systems Research*, (196), pp. 107-122.

Ferraz, R., Iurinic, L., Filomena, A., Gazzana, D., Bretas, A.(2016). Arc fault location: A nonlinear time varying fault model and frequency domain parameter estimation approach. *International Journal of Electrical Power & Energy Systems*, (137), pp. 347-355.

Fișcă, M., Abrudean, M., Muresan, V., Clitan, I., Ungureșan, M., Motorga, R,. and Ceuca, E. (2023). Modeling and Simulation of High Voltage Power Lines under Transient and Persistent Faults. *MDPI Mathematics*, (11), pp. 1-28.

Fișcă, M., Abrudean, M., Mureșan, V., Ungureșan, M., Clitan, I., Cordoș, R. and Stăncioi, C. (2023). Modelling and Control of the ^{18}O Isotope Separation Plant. *Journal of Control Engineering & Applied Informatics*, (25), pp. 101-112.

Mureșan, V., Abrudean, M., Moga, D., Petreus, D., Stroia, N., Bondici, C., Fișcă, M. and Cohuț, M. (2022). Fault Tolerant Control System for a Mini Hydropower Plant. *11th IFAC Symposium on Control of Power and Energy Systems*, (55), pp.537-542.

Radojević, Z.(2007). A new spectral domain approach to the distance protection, fault location and arcing faults recognition on transmission lines. *International Journal of Electrical Power & Energy Systems*, (29), pp. 183-190.

Rusu, I., Lupu, I. and Sufleţel, N. (2009). *Aerial electrical networks*, pp. 136-246, Lucid Serv., Iași, Romania.

Tarko, R., Gajdzica, J., Nowak, W., and Szpyra, W. (2021). Comparative Analysis of High-Voltage Power Line Models for Determining Short-Circuit Currents in Towers Earthing Systems.*MDPI Energies*, (14), pp. 1-19.

Vulcu, I. (2007). *Single-phase fault – Identification, location, display*, pp. 82-207, Matrix-Rom publishing house, Bucharest, Romania.