Design of a Very Low Frequency Test Device for Faults Diagnosis in Underground Cable

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Abstract: In this paper, we present the design of a Very low frequency (VLF) generator made of power electronics converter coupled to a mechanical system. This device is used to detect and locate faults in cables. This VLF test is an AC type test at 0.1 Hz of a cosine-rectangular waveform performed on an underground cable. Simulations were carried out for the following cable faults: open-circuit, short-circuit, resistance fault and spark gap. For each fault type, simulations are performed for different locations in order to collect databases in a neural network relating the distance and the corresponding voltage from the fault location. This allows to register the range of voltages variation in each fault, which is useful for its identification. In addition, these databases are used to determine the fault location using the Spline interpolation method. The tests were performed on a 20 km cable length. The obtained results show the high performance and efficiency of the investigated methods in terms of cable fault identification precision and localization.

1 INTRODUCTION

Overhead lines and underground cables provide energy transport from power generation plants. Distribution underground networks and especially transmission networks are undergoing rapid development imposed by the growth of urban areas on the one hand and on the other hand for a better quality of service and environment required by the citizen consumer of electricity. The structure of the cables directly influences the number of measurements to be carried out to characterize the types of faults (H. KUZYK, 2006).

Compared to overhead lines, the structure of underground cables is complicated by the presence of metal shielding near the central conductor. Therefore, the inductive and capacitive effects are of extreme importance, which requires special attention when calculating the physical parameters of underground cables such as resistances, chokes and mutual inductances as well as capacitances (M. Pays, 1994). In addition, underground electricity cables have many advantages compared to overhead lines. Indeed, they require virtually no maintenance and above all are not affected by hard weather conditions. On the other hand, and from an operational point of view, repairing time of a faulty cable is relatively long due to time-differed steps necessary for fault location and troubleshooting procedure.

The electricity transmission network, especially, using underground cables is never immune to electrical incidents due to internal and external origins, causing blackouts. These faults are mostly from external origin due to earthmoving works (H. KUZYK, 2006). When an incident occurs, the direct consequence is the power outage. It is therefore appropriate for the power company to ensure the restoration of electrical energy as soon as possible, hence the need to identify the types and locations of faults. The faults types are classified mainly into four families which are open-circuit, short-circuit, resistance and spark gap faults.

In order to ensure the continuity of electrical power supply, electricity companies seek to identify and locate the faulty cable segment with a good precision in a short time in order to reduce downtime. This can only be achieved by implementing simple, fast and precise pre-location techniques based on an exact determination of the physical parameters of the cable in order to reduce repairing time and cost. The different operating

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disturbances observed in the electrical networks lead, in most cases, power cuts and a important number of incidents, which are due to external injuries or internal breakdowns of cables or their accessories.

Currently, diagnostic methods are developed and used in a several sectors such as cable faults and power converters faults (M.A. Zdiri et al., 2019; M.A. Zdiri et al., 2019; M.A. Zdiri et al., 2020). The main goal of diagnostic techniques is to prevent downtime during maintenance on electric network, independently to its voltage level. It will allow the operator to determine accurately the cable state (effects of aging, degree of humidity, or even water trees) and to warn operator about the deterioration on the insulation of medium and high voltage cables by using the dielectric diagnostics (TAN) and the partial discharge (DP) (H. KUZYK, 2006). The nature of a fault can easily be determined by simple methods of measuring insulation resistance and conductor continuity. The cable tests goal consist to explore new installations (commissioning, checking junction and ending boxes) during repair works. The tests can be carried out with direct current or (VLF) alternative current (M. Baur, 2008). The VLF method, recently developed for cables in synthetic material, has also proved its effectiveness for cables insulated with impregnated paper. In addition, it allows a much more interesting and precise diagnosis, which made its success and incorporation into European standards (Norme, DIN VDE, 1995). In (H. Oetjen, 2004), the authors compare different VLF techniques related to the correlation between the data of test field and test parameters. Furthermore, a new design and realization of a VLF technique based on 0.1 Hz sinusoidal waveform is presented in (S. Seesanga et al., 2008). In order to detect and identify cables faults in medium voltage, the authors in (B.V. Wong et al., 2016) investigate the VLF test combined with Tan Delta and Partial Discharge. In addition, the authors in (C. Xie et al., 2018) highlighted the capacity of the main VLF testing methods for the cables XLPE (Cross-linked polyethylene) of newly installed 10 kV in approval tests. Meanwhile, the failures of insulation of XLPE cables have become a hard security hazard. The authors in (X. Tan et al., 2019) propose a new type of 0.1 Hz VLF sinusoidal waveform generator that is characterized by a novel control and simple structure.

Despite the existence of different methods in literature, there is still a lot to be done in order to develop new methods to improve the reliability of underground cables. In this paper, we have proposed a cosine-rectangular waveform VLF device at 0.1 Hz, based on power switches, to detect and identify the faults of an underground cable with 20 km length. Using this VLF generator, we tested four types of faults, which are open-circuit fault, short - circuit fault, resistance fault and spark gap fault. These different tests are stored in the neural network, which make it possible to identify the type of fault. In addition, the Spline interpolation method was used for each voltage range corresponding to a specific fault type. Therefore, the detection, identification and localization of the cable fault, these done based on the neural network and the Spline method.

In conclusion, the simulation results prove to verify the high performances of these methods in terms of detection and identification precision of cables faults.

2 DESIGN OF A 0.1 Hz VLF GENERATOR FOR TESTING CABLE FAULTS

As seen previously, we have listed the different types of HVA underground cable for fault location tests. Subsequently, we will focus our study on a very precise and revolutionary test, which is the VLF test. Therefore, we will study the operation of the VLF test device and we will try to design a new device and improving it by mean of simulation for verification. A very low frequency dielectric test will check the dielectric state of a polymer cable. In this section, we will give the operation principle of a cosine-rectangular VLF device and propose another device allowing to obtain the same desired waveform at the output.

2.1 Constitution

The VLF test is featured in several applications with slow detection time for weak spots on synthetic cables (PE/XLPE) and paper cables (PILC) and also excess stress in (BAUR) cables. The cosine-rectangular VLF waveform is patented and approved by the CEI and IEEE organizations. A VLF device generally consists of an HVA DC test unit generator, a storage coil, an electronic switch (rotary rectifier), a voltmeter, a discharger switch and a support capacitor.

2.2 Operation

The VLF test does not damage the cable structure, however, it does cause rapid growth of electrical treeing if they exist. Compared with other test devices, VLF devices have lower weight and lower power consumption along with higher test reliability. The figure 1 illustrates the voltage curve characterizing a device of the 0.1 Hz VLF test.

The principle of operation is based on the position of the rotary diode based rectifier and the charging and discharging of a capacitor. We can remark that at an operation state corresponding to an angle multiple of 72° and a well-defined time. After a complete turn of the device (passage of the five stages), we can observe the waveform at the exit of the capacitor (charge and discharge). Based on the operating sequences, an equivalent circuit is modelled and the operating equations are sorted for each step sequence.

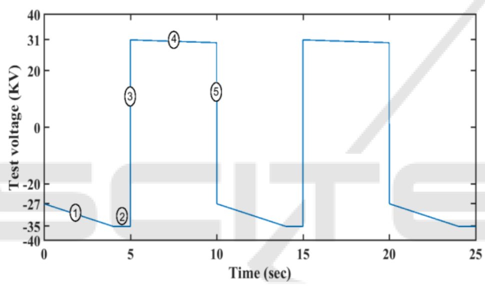

Figure 1: Voltage curve characterizing a 0.1 Hz VLF test device.

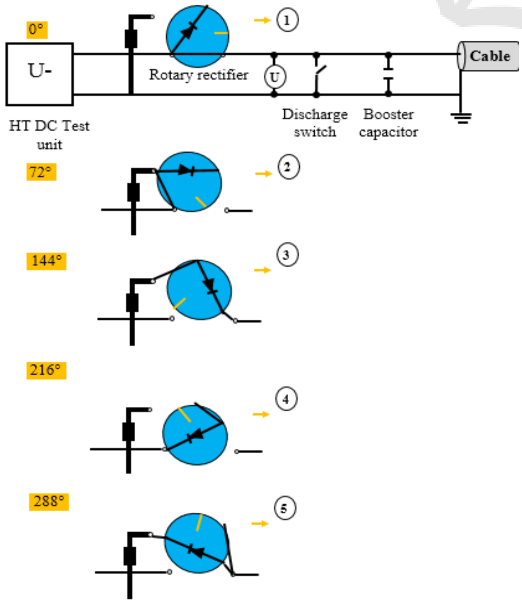

Figure 2: Different rotating rectifier position sequences of a VLF device.

Different rotary rectifier positions associated to the VLF generator are shown in figure 2.

2.3 Design of a New Cable Fault Test VLF Generator

After showing the operation principle of the classical VLF device, we will propose another type of VLF device made up of totally controlled components as shown in figure 3. In this paper, we have focused our study only on the VLF generator at 0.1 Hz. It is to be noted that this new VLF generator is based on IGBT's and diodes. In order to design this device, we have chosen the following values: Vdc = 40 kV; L = 0.1 H; R1 = 0.001 Ω; C = 0.001 F; R2 = 0.1 Ω.

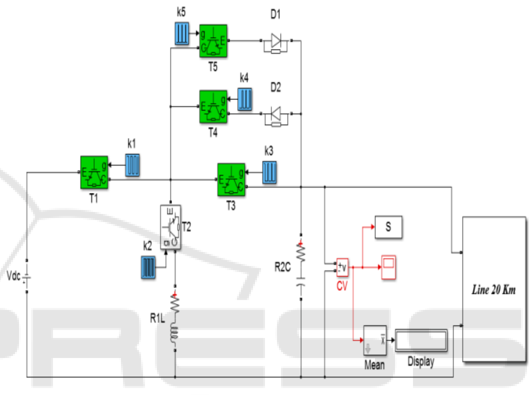

Figure 3: Model of the new proposed 0.1Hz VLF device.

The table 1 gives the different switching intervals of each power device for a switching frequency equal to 0.1 Hz.

Table 1: Power switches Control at 0.1 Hz.

time (s)	[0-2]	[2-5]	[5-6]	[6-8]	[8-10]
k1	On-state	On-state	Off-state	Off-state	Off-state
k2	Off-state	On-state	On-state	Off-state	On-state
k3	On-state	Off-state	Off-state	Off-state	Off-state
k4	Off-state	Off-state	Off-state	Off-state	On-state
k5	Off-state	Off-state	On-state	Off-state	Off-state

In order to apply the proposed VLF generator to a cable, we will choose a 20 km unipolar one decomposed into 10 portions of 2 km with own linear characteristics impedance. This VLF generator is used in order to see the behaviour of the output signal during tests on a healthy and faulty cable. The figure 4 represents the equivalent model of a 20 km underground cable subdivided into 10 blocks of 2 km length each.

Table 2 illustrates the actual characteristics of an underground cable from the manufacturer PIRELLI which can withstand a voltage of 40 kV with an aluminium conductive core with PR insulator, direct current resistance R = 0.125 Ω/km at 20 °C, self-induction L = 0.38 mH/km and capacitance C = 0.212 μF/km.

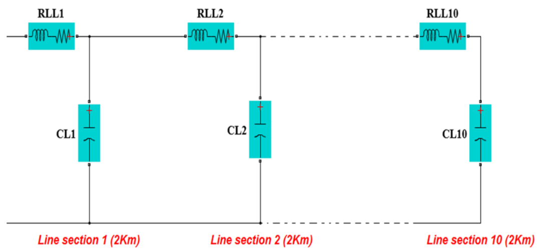

Figure 4: Model of a 20 km electric cable.

Table 2: Characteristics of an ALU-PR cable.

Builder	Voltage (kV)	Type	Impedance		
PIRELLI	18/30 (36)	1*240 ALU-PR	DC resistance (Ω/km) (at 20 ° C)	Self-induction for external cable (mH/km)	Capacity (μF/km)
			0.125	0.38	0.212

3 SIMULATION RESULTS

As mentioned before, the most common faults affecting underground cables are open-circuit, short-circuit, resistance and spark gap faults as presented in figure 5. To locate the fault of an underground cable, we carried out tests on a cable of length 20 km. We registered the fault results for different cable distances. Indeed, we determine for each distance the mean voltage corresponding to it. We built a database consisting of the different values of the average voltages that the cable can withstand for well-defined lengths.

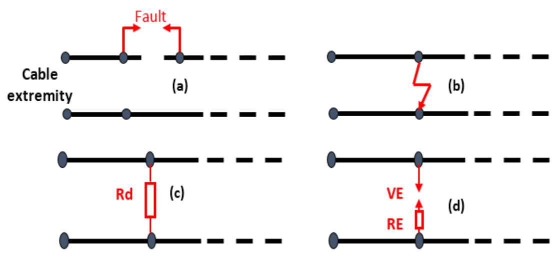

Figure 5: (a) Open-circuit fault. (b) Short-circuit fault. (c) Resistance fault and (d) Spark gap fault.

Moreover, we then applied the cubic spline interpolation method (Schumaker, 2007) according to the values of the obtained faults. The investigation phase of the interpolation method consists in being able to determine the exact location of the failure on the cable by measuring the voltage value at its input. This procedure will be applied in the different simulations of the cable faults.

In the healthy case of the cable, we applied the signal from the VLF at 0.1 Hz generator to a healthy cable of 20 km long. Figure 6 shows the waveform of the voltage at the input of the cable.

The average value of the voltage in the healthy or faulty case is determined by the following expression:

$$V_{moy} = \frac{1}{T}\int_0^T V(t)dt \qquad (1)$$

Furthermore, table 3 illustrates the voltage average value of a cable with 20 km long.

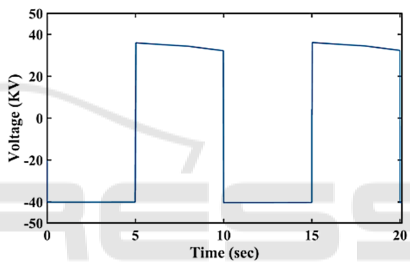

Figure 6: Waveform of the voltage terminals across a healthy cable at 0.1 Hz.

Table 3: Simulation results on a healthy cable.

Cable length	Voltage average value (V)
20 km	-2947.86 V

3.1 Open-circuit Fault

In simulation, we are going to use a breaker in order to apply the cable open-circuit fault. For a fault located at a distance equal to 2 km, we obtain the voltage signal shown in figure 7.

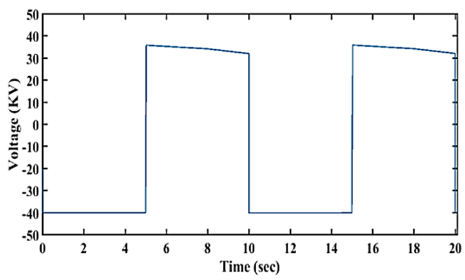

Figure 7: Voltage signal due to the opening of a 2 km line portion.

The table 4 shows the different average values of each cable section with an open-circuit fault.

In order to determine the intermediate points, we applied the Spline method. Thus, we brought out the interpolation of the voltage curve corresponding to the open-circuit of a cable portion, as shown in figure 8.

Table 4: Simulation results due to an open-circuit fault in a cable portion.

Cable portion Cutout location (km)	Voltage average value (V)
2	-2955.02
4	-2954.71
6	-2953.98
8	-2953.27
10	-2952.13
12	-2951.06
14	-2950.31
16	-2949.52
18	-2948.64
20	-2947.86

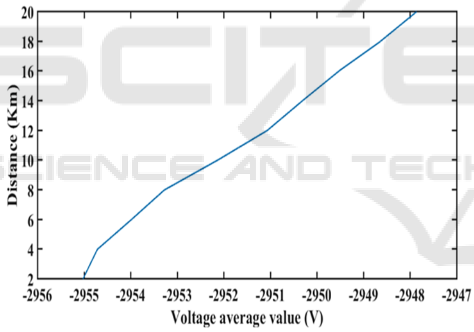

Figure 8: Interpolation curve of the opening fault of a 20 km cable.

3.2 Short-circuit Fault

The short circuit fault is achieved by applying a signal equal to '1' to the breaker, which is connected in parallel with the rest of the cable. For a fault in 20 km cable length, the voltage signal is obtained as shown in the figure 9.

Table 5 shows the different voltage average values for each cable portion with a short-circuit fault. In order to determine the intermediate points of this fault type, we applied the Spline method. Thus, we brought out the interpolation curve of the short-circuit fault of cable, as shown in the figure 10.

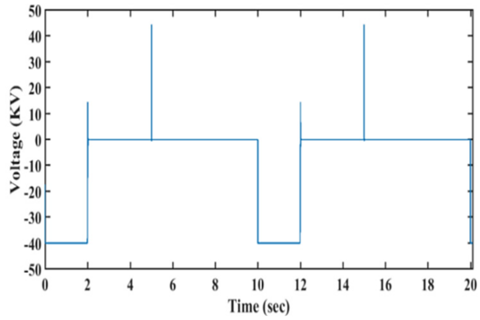

Figure 9: Voltage signal for a short-circuit fault appearing at the end of 20 km cable length.

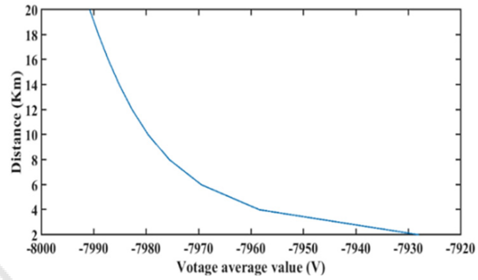

Figure 10: Interpolation curve of the short-circuit fault of a 20 km cable.

Table 5: Simulation results of voltage signal with a short-circuit fault in a cable portion.

Cable short circuit location (km)	Voltage average value (V)
2	-7927.95
4	-7958.36
6	-7969.45
8	-7975.53
10	-7979.60
12	-7982.65
14	-7985.1159
16	-7987.2172
18	-7989.0752
20	-7990.7630

3.3 Resistance Fault

The resistance fault in a cable is ensured by using a priming resistance Rd = 100 Ω. For a fault located at a distance of 2 km, the output voltage signal is obtained as shown in the figure 11.

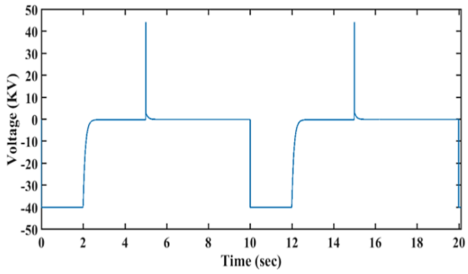

Figure 11: Voltage Signal due to a resistance fault between portion 1 and 2 of a 20 km cable.

Table 6: Simulation results on a cable with resistance fault of a section.

Cable Portion Resistance fault location (km)	Voltage average value (V)
2	-8393.72
4	-8394.84
6	-8395.96
8	-8397.08
10	-8398.20
12	-8399.32
14	-8400.45
16	-8401.57
18	-8402.69
20	-8403.81

The table 6 shows the different average values for each section with a resistance fault.

In order to determine the intermediate points, we applied the Spline method. Thus, we brought out the interpolation curve of the resistance fault of a cable section, as shown in the figure 12.

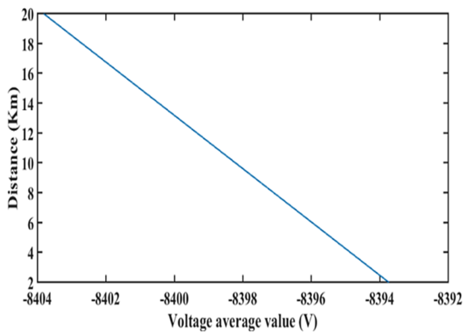

Figure 12: Interpolation curve due to a resistance fault of a 20 km section.

3.4 Spark Gap Fault

We will apply a voltage signal for the cable spark gap fault at the distance 20 km with a priming resistance RE = 100 Ω and a priming voltage VE = 20 kV. For a spark gap fault located at a distance of 20 km, the output voltage signal is obtained as shown in figure 13.

Table 7 shows the voltage average values of each section with spark gap fault. Then, in order to locate the fault more precisely, we applied the Spline method. Thus, we brought out the interpolation voltage curve corresponding to the spark gap fault of a cable portion as shown in figure 14.

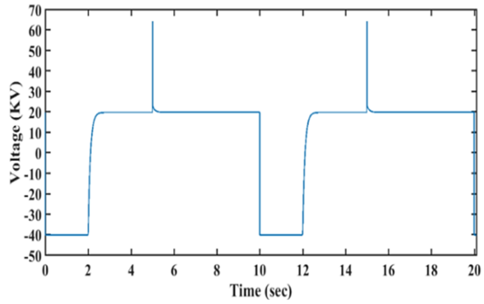

Figure 13: Signal of a spark gap fault at the end of 20 km cable.

Table 7: Simulation results on a spark gap fault of a cable section.

Cable Portion spark gap fault position (km)	Voltage average value (V)
2	7370.98
4	7369.20
6	7367.43
8	7366.66
10	7363.88
12	7362.11
14	7360.33
16	7358.56
18	7356.79
20	7355.01

3.5 Identification and Localization of Fault

In order to identify and locate the different faults, we will pursue the following steps:

- Build databases for the different fault types;
- Applies the Artificial Neural Network ANN (A. Maheshwari et al., 2018) to determine the type of fault. This is done by determining for each fault the range of variation of the average voltage. In the ANN technique, the output indices 1, 2, 3 and 4 can be assigned for open-circuit fault, short-circuit fault,

resistance fault and spark gap fault. The ANN model is shown in the figure 15.

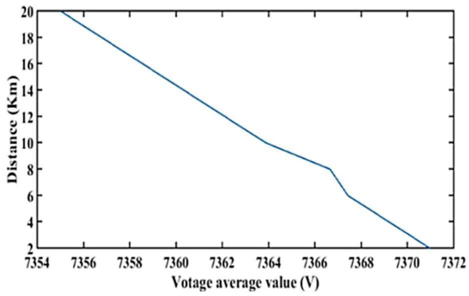

Figure 14: Interpolation curve of the spark gap fault at the end of 20 Km cable.

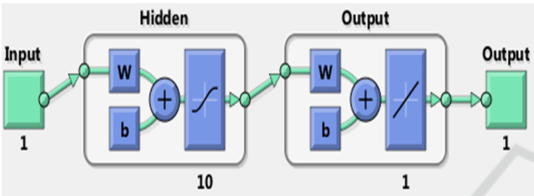

Figure 15: ANN model.

To test the performance and effectiveness of these used methods, a test was performed for a four random values of average voltage. The identification technique gives the results shown in table 8. From the identified defaults locations this table shows the exact values of the voltages from the direct tests on the cable and by using the used VLF generator. The comparison between these voltages values proves the high performance and efficiency of the proposed method.

Table 8: Identification and localization of studied faults.

Voltage average value (V)	Fault identification	Default Localization (km) (from Neural Network and Spline)	Exact average voltage (V) corresponding to the identified localization
-2950	Open-circuit	14.8293	-2950.6853
-7970	Short-circuit	6.1458	-7970.0029
-8400	Resistance	13.1980	-8400.1066
7365	Spark gap	9.6556	+7365.5748

4 CONCLUSION

An energy transmission network, even underground, is exposed to electrical incidents causing the shutdown of the electricity supply. Improving the quality of service is essentially depending on the speed and precision with which a fault is located. To do this, we studied the VLF device to detect and identify High Voltage of type A underground cable faults. In this paper, the VLF method is investigated since it has a wider detection range and less aggressive for underground cables.

Subsequently, we gave a new electronic version of the VLF device based on the operating steps of power switches. Thus, we have modelled an underground cable with real parameters, in order to simulate the different types of faults most frequently observed. A database by performing faults for different distances and for each type of fault is performed using the neural network. In order to detect precisely these different types of faults, we have proposed the Spline interpolation method.

Simulations were done using MATLAB/Simulink. As conclusion, the results obtained are very interesting and promising in terms of detection, identification and localization of distinct fault type in underground cables.

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