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Analysis of the effectiveness of relative methods for power cable fault detection

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Abstract. The aim is to evaluate the effectiveness of relative methods used to locate faults of 6–10 kV power cables operated at an industrial enterprise. To achieve this goal, the reflectograms obtained on damaged power lines were compared with the reference ones. The research object is represented by three 6–10 kV power cables with paper-oil insulation, 900–3000 m long, and with a service life of more than 30 years. The type of damage to all power lines was a single-phase creeping discharge. The study employed various methods (TDR, ARC, ICE/Decay) to locate faults in the lines and the test rigs. The equipment used to detect cable fault locations included a REIS-305 reflectometer, a GVI 24.3000IDM high-voltage pulse generator, and a SDC50 current sensor. Multiple soundings of the power lines under study were performed to obtain reflectograms containing information about the distance to the fault location. As a result of the conducted research, varying in informativeness reflectograms of power cables were taken. We managed to select the true ones from them. Serious discrepancies in the shape of the displayed sounding pulse in the reflectograms were identified in comparison with the reference ones given in relevant technical literature. The article highlights issues concerning the application of the ARC method. The challenges consist in the breakdown voltage limitation at the cable faults. Each cable fault is shown to have its own characteristics. However, their causes are difficult to identify since it is impossible to establish the process of and the prerequisites for electric current passage when a short circuit arises. Drawing on the results of the undertaken study, a recommended algorithm was developed to determine the distance to the location of a power cable fault. However, due to the small amount of scientific research on this subject matter, no absolutely universal approach to this problem exists at present; its creation requires further investigation.

Keywords: fault location, cable line, reflectometer, reflectogram, creeping discharge, TDR, ICM, ARM

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ЭНЕРГЕТИКА

Научная статья
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Анализ эффективности относительных методов поиска повреждений кабельных линий

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Резюме. Цель – оценить эффективность применения относительных методов определения мест повреждений кабельных линий 6/10 кВ, эксплуатируемых на промышленном предприятии, на основе сравнения рефлектограмм, полученных на поврежденных кабельных линиях, с эталонными. Объектом исследования служили три кабельные линии 6/10 кВ с бумажно-масляной изоляцией длиной 900–3000 м и со сроком эксплуатации более 30 лет. Тип повреждения всех кабельных линий – однофазный заплывающий пробой. В работе использовались различные методы поиска мест повреждений линий и применяемых испытательных установок: импульсный, импульсно-дуговой, метод колебательного разряда по току. В качестве оборудования для поиска мест повреждений выступали рефлектометр РЕЙС-305, ударная установка ГВИ 24.3000ИДМ и присоединительное устройство по току SDC50. Производились многократные зондирования исследуемых кабельных линий с целью получения рефлектограмм, имеющих информацию о расстоянии до места повреждения. В результате проведенных исследований были сняты рефлектограммы кабельных линий различной информационной ценности, среди которых удалось отобрать истинные. Выявлены серьезные расхождения в форме отображаемого зондирующего импульса в рефлектограммах по сравнению с эталонными, приведенными в технической литературе. Отмечены проблемы при применении импульсно-дугового метода, заключающиеся в ограничении по напряжению пробоя в месте повреждения. Также показано, что каждое место повреждения имеет свои особенности, причины которых являются сложновыявляемыми ввиду невозможности установить процесс и предпосылки протекания тока в момент возникновения короткого замыкания. По результатам проведенных исследований был составлен рекомендуемый алгоритм действий при определении расстоянии до места повреждения кабельной линии. Однако ввиду малого количества научно-исследовательских работ по данной тематике абсолютно универсального подхода к определению мест повреждения кабельных линий в настоящий момент не существует, и его создание требует поведения дальнейших исследований.

Ключевые слова: определение места повреждения, кабельная линия, рефлектометр, рефлектограмма, заплывающий пробой, TDR, ICM, ARM

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INTRODUCTION

One of the key issues in the operation of power cable lines (CL) is locating faults [1]. Currently, in the Russian Federation, the personnel of electrotechnical testing laboratories (ETL) use a specific set of absolute and relative methods to locate faults in CL [2]. When analyzing the configurations of modern mobile ETLs, as well as the market for fault location devices, it can be concluded that the relative method of impulse reflectometry is gaining popularity, while a number of methods such as the loop and capacitive methods are used extremely rarely or not used at all [3, 4]. Modern reflectometers are technically sophisticated devices that combine several methods for fault location in cable lines (CL) [5]. At the same time, ongoing improvements are being made in the methodology [6, 7], technology [8, 9], equipment [10, 11], and mathematical frameworks [12–14] methods used for fault location techniques. However, the primary method for identifying the fault zone in 6–10 kV CL remains the use of a reflectometer that implements the following techniques: Time-Domain Reflectometry (TDR), Impulse Current Method (ICM), Voltage Decay Method (Decay), and Arc Reflection Method (ARM) [4, 15]. The relevance of this study lies in the fact that current research scarcely addresses the problem of the analysis of reflectograms for the relative determination of fault locations in operational CLs. Therefore, the aim of this study is to evaluate the efficiency of fault zone locating methods using 6–10 kV CL in operation at an urban industrial enterprise.

METHODS

The methods for determining the distance from the measurement point to the fault location are called relative methods. Relative methods do not guarantee high accuracy in pinpointing the fault location. However, they indicate the zone where the fault exists and enable the use of absolute methods within this zone. Absolute methods are those by which the fault location can be determined directly [2].

The paper considers reflectograms obtained using the following relative methods: TDR[4], ICM[5], ARM[6]. Relative methods for fault location are ways to determine the so-called fault zone. Their essence lies in determining the approximate distance to the fault in the cable line by connecting the instrument at one end of the line. Once the approximate fault zone is known, acoustic fault location techniques are applied within that zone. Preliminary identification of the fault zone is critically important, since 6–10 kV CL can be very long [15–22].

[3]RD 34.20.516-90. Guidelines for locating faults in power cables with voltage up to 10 kV. Moscow: ORGRES; 1991, 41 p. / РД 34.20.516-90. Методические указания по определению места повреждения силовых кабелей напряжением до 10 кВ. М.: ОРГРЭС, 1991. 41 с.

[4]Time-domain reflectometry (TDR) method. Theoretical foundations. Available from: https://www.ersted.ru/stati/reflektometrija/osnovyi-reflektometrii/ [Accessed 1st March 2025] / Метод импульсной рефлектометрии (TDR). Теоретические основы. Режим доступа: https://www.ersted.ru/stati/reflektometrija/osnovyi-reflektometrii/ (дата обращения: 01.03.2025).

[5] Impulse current method (ICE/Decay) for detecting high-resistance faults. Available from: https://www.ersted.ru/stati/reflektometrija/metod-kolebatelnogo-razryada-ice-decay-opredeleniya-vyisokoomnyih-povrezhdeniy/ [Accessed 1st March 2025] / Метод колебательного разряда (ICE/Decay) определения высокоомных повреждений. Режим доступа: https://www.ersted.ru/stati/reflektometrija/metod-kolebatelnogo-razryada-ice-decay-opredeleniya-vyisokoomnyih-povrezhdeniy/ (дата обращения: 01.03.2025).

[6]Arc reflection method (ARM) for detecting high-resistance faults. Available from: https://www.ersted.ru/stati/reflektometrija/vyisokoomnyiy-defekt/ [Accessed 1st March 2025] / Импульсно-дуговой метод (ARM) определения высокоомных повреждений. Режим доступа: https://www.ersted.ru/stati/reflektometrija/vyisokoomnyiy-defekt/ (дата обращения: 01.03.2025).

The object of study comprises three 10 kV CL with isolated neutral and paper oil insulation at a large enterprise located within an urban area of a metropolis. Cable lengths range from 900 m to 3000 m (Table).

All faults are single phase creeping discharges to ground, with transition resistance ranging from hundreds of kΩ to tens of MΩ and discharge voltages of 5–10 kV. These cable lines have been in service for over 30 years, which, according to GOST standards, exceeds the minimum service life[7].

The equipment used for fault location included GVI 24.3000IDM units, the SDC50 current connection device, and the REIS 305 reflectometer. Connection diagrams for each method and sample reflectograms are shown in Figs 1–3. For analysis and annotation of the reflectograms, we introduce a common marking to indicate pulse deviations: cursor 0 (the line start in ARM and TDR, and the start of the oscillatory interval in ICM) is marked by a green rhombus; cursor 1 (the fault location in ARM and TDR, and the end of the oscillatory interval in ICM) is marked by a red square; and the end of the cable line is marked by a blue circle.

TDR is the probing the CL with voltage pulses from the reflectometer, followed by receiving pulses reflected from the fault location and inhomogeneities in characteristic impedance, and determining the distance to the fault on the obtained reflectogram.

CL characteristics
Характеристики CL

No. CL	Length ≈, м	Approximate number of splices per km	Type of fault	Transition resistance, MΩ	Discharge voltage, kV	Distance to fault location, m
1	3000	16	Single phase creeping discharge	0,1–30 Fluctuating	5–10 Fluctuating	~2400
2	2950	8				~1800
3	920	10				~430

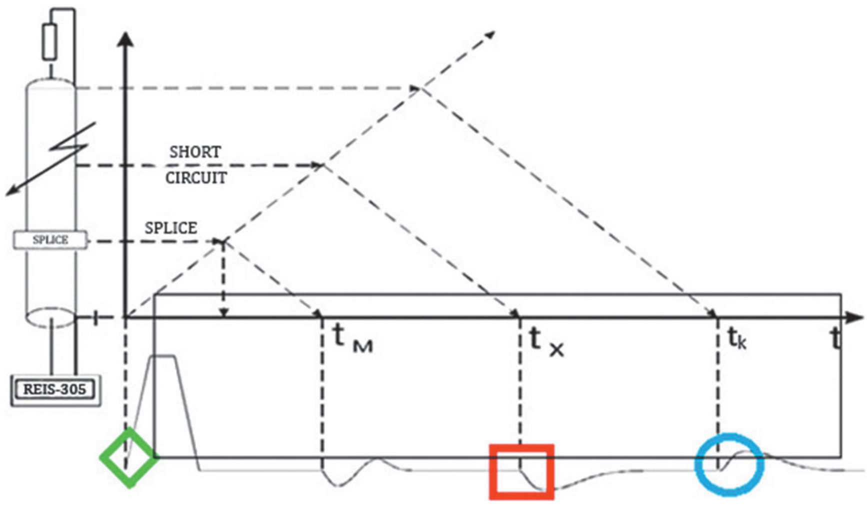

Fig. 1. *Connection diagram and reflectogram of the TDR method*
Рис. 1. *Схема подключения и рефлектограмма TDR метода*

[7]GOST 18410-73. Power cables with impregnated paper insulation. Specifications. Introduced on January,1 1975 (replacing GOST 340-59, GOST 6515-55). Moscow: Publishing House of Standards, 1998. / ГОСТ 18410-73. Кабели силовые с пропитанной бумажной изоляцией. Технические условия. Введ. 01.01.1975 (взамен ГОСТ 340-59, ГОСТ 6515-55.). М.: Изд-во стандартов, 1998.

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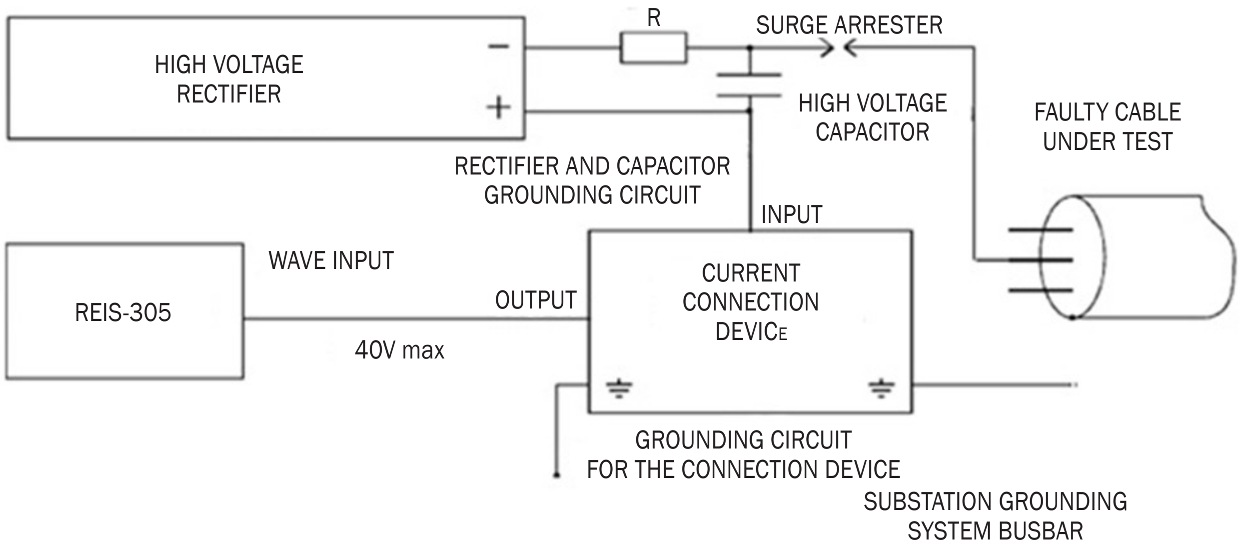
A splice is displayed by alternating negative (down) and positive (up) pulse polarity (time t_m). A short circuit is displayed by a negative polarity pulse (time t_x). The end of the line or an "open circuit" type defect is displayed by a positive polarity pulse (time t_k). Only the REIS-305 is used for the implementation of this method.

ICM is a method when a discharge caused by a surge generator induces an oscillatory discharge process (decaying wave process). The device records these oscillations and outputs a current waveform (hereafter referred to as reflectograms in the text). The distance is measured between characteristic downward drops of the impulse, which represent the period of the oscillatory process. Methodological guidelines recommend using the second period – between the second (green rhombus in Fig. 2) and third (red square in Fig. 2) downward drops. This interval reflects the distance to the damage location. This method employs the GVI-24.3000IDM in standard acoustic mode, the SDC50 current connection device, and the REIS-305 reflectometer.

ARM is a method when a discharge induced by a surge generator creates an electrical arc at the cable fault, the low impedance of which reflects the device probing impulse analogous to TDR. The method also involves comparing the reflectogram obtained by conventional TDR before the discharge with



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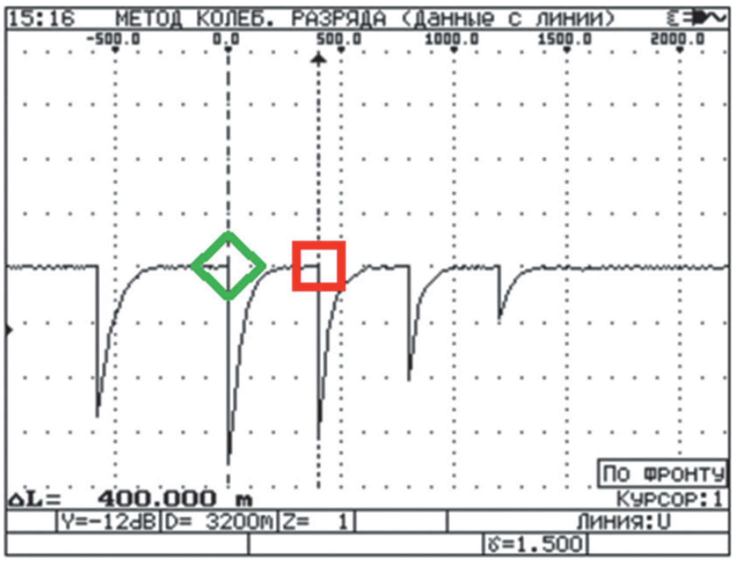
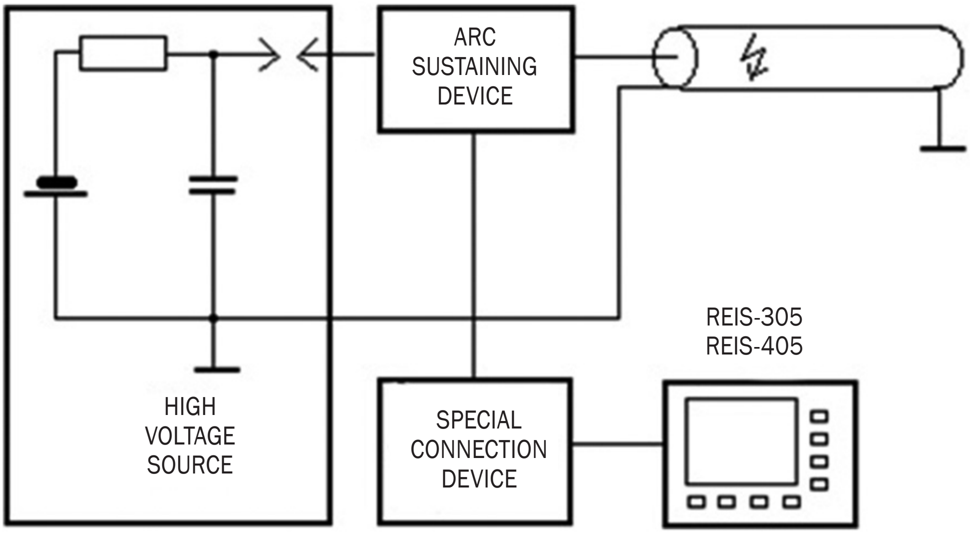
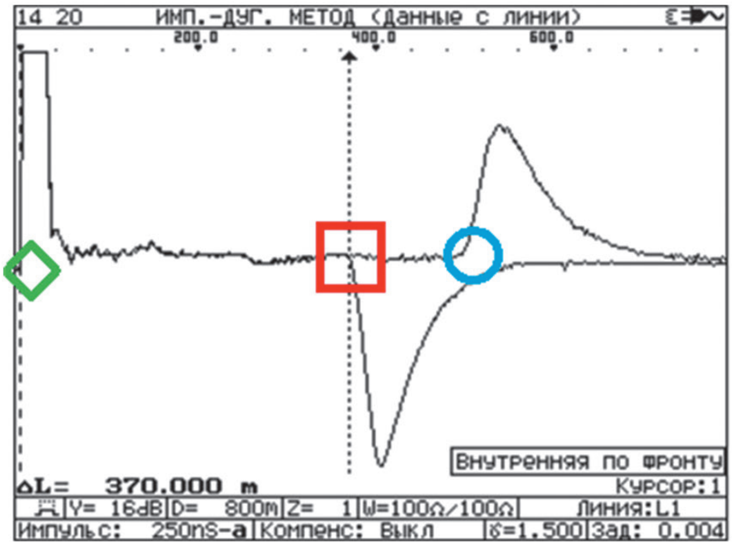


b

Fig. 2. *Connection diagram and reflectogram for the ICM method: a – connection diagram; b – reflectogram*
Рис. 2. *Схема подключения и рефлектограмма ICM метода: a – схема подключения; b – рефлектограмма*



a



b

Fig. 3. *Connection diagram and reflectogram for the ARM method: a – connection diagram; b – reflectogram*
Рис. 3. *Схема подключения и рефлектограмма ARM метода: a – схема подключения; b – рефлектограмма*

the ARM reflectogram after the discharge, both displayed simultaneously on the device screen. The fault location is identified by the characteristic significant downward deflection of the pulse (red square in Fig. 3) relative to the pre discharge reflectogram. Because the arc extinguishes rapidly, an arc-sustaining choke is used as part of the surge generator to allow it to be detected by the probing signal. This method is implemented using a GVI 24.3000IDM unit in impulse arc mode and the REIS 305 reflectometer.

One feature of the REIS 305 in ARM mode is the ability to probe the CL with multiple pulses (up to ten), each with configurable start times and inter-pulse intervals.

Currently, ARM has become the predominant fault zone locating method due to its simplicity and high accuracy [16].

RESULTS

TDR on all investigated cable lines did not produce reflectograms that allowed determination of the distance to the fault location, which is due to high transition resistance and a large number of inhomogeneities in the CL.

On the first cable line (CL No.1), it was not possible to achieve a stable, readable reflectogram when working in ARM mode (Fig. 4), which shows two impulses – ARM and TDR respectively. Adjustments to signal gain and varying the timing intervals of the probing pulses (measurements) also did not yield results. One of the conditions for confirming the validity of a reflectogram when working with this method is its multiple repetition during a series of discharges at the fault location. Besides the absence of a characteristic strong impulse reflection with negative polarity, a comparable positive polarity impulse can also be observed, as well as a series of inhomogeneities at the beginning of the line. It is impossible to interpret this reflectogram unambiguously, so it was decided to utilize the ICM method; a stable, readable reflectogram was obtained through a series of discharges (Fig. 5).

It is worth noting that the appearance of the reflectogram differs significantly from the one provided in the device operating manual – downward peaks are followed by upward peaks[8]. However, considering the distinct downward drops at the location of the green

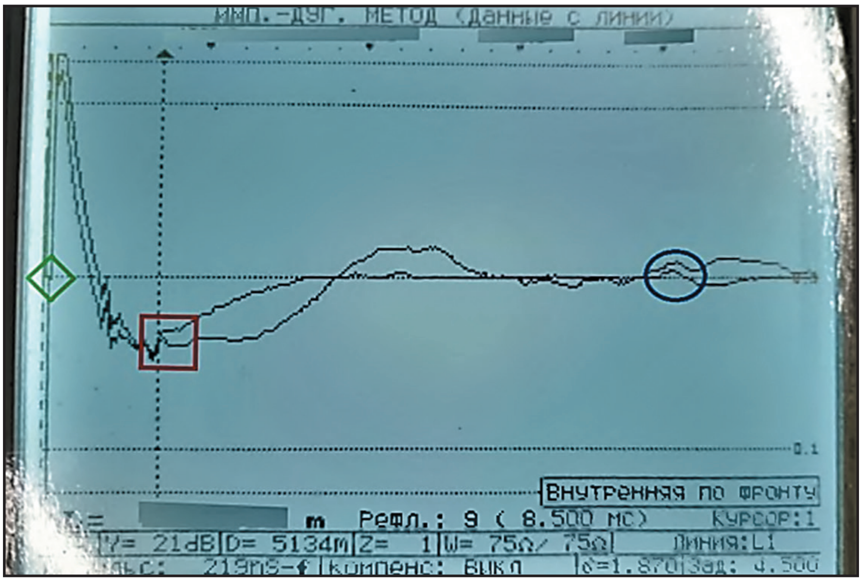


Fig. 4. *Reflectogram when using ARM on CL No. 1*
Рис. 4. *Рефлектограмма при использовании ARM на CL № 1*

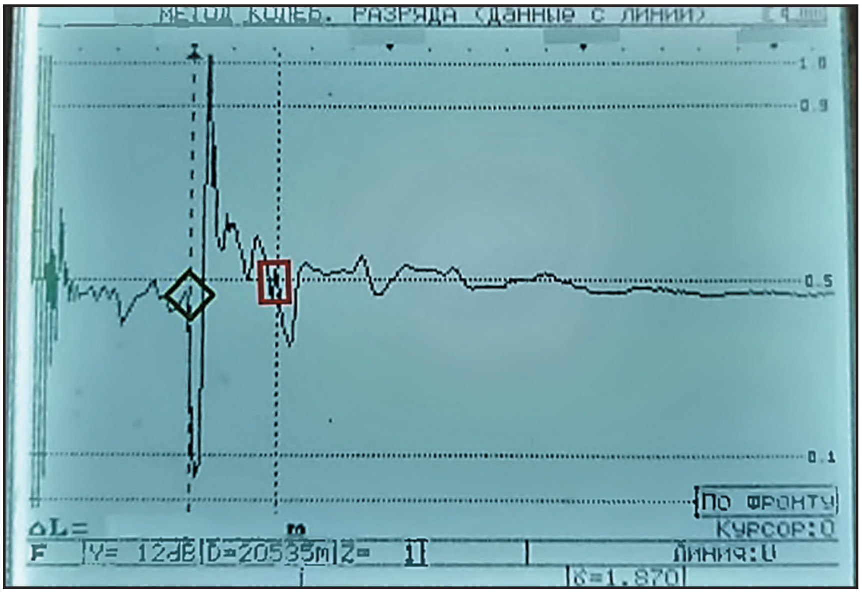


Fig. 5. *Reflectogram when using ICM on CL No. 1*
Рис. 5. *Рефлектограмма при использовании ICM на CL № 1*

[8]REIS-305 Reflectometer. Operation manual. Bryansk: Electrical line testing systems, 2014. 86 p./ Рефлектометр РЕЙС-305. Руководство по эксплуатации. Брянск: Системы тестирования электрических линий, 2014. 86 с.

rhombus and the red square, it was decided that this reflectogram was valid, after which the ARM method was applied again. The ICM made it possible to determine at what distance the correct negative polarity pulses are located.

Repeated application of the ARM method still did not yield a stable or accurate reflectogram; however, knowing the approximate distance from two previous discharges made it possible to obtain the reflectogram shown in Fig. 6.

It is worth noting that during the previous procedures, the discharge voltage in CL No.1 decreased to 5–6 kV. Based on the results in Figs. 5 and 6, a decision was made to define the fault zone. Further on-site determination using the acoustic method confirmed the results obtained from both the ARM and ICM methods. Notably, in this case, the readings from the two methods coincided within 0.1 meters.

For CL No. 2, series of repeated reflectograms were obtained using the ARM method. Fig. 7 shows three of the most stable and readable reflectograms for comparison with the ICM method. Based on the results, it was difficult to determine the fault location due to their inconsistency, as the presumed fault zone (red square) is located at different distances.

ICM in this situation had a less readable reflectogram; however, considering the shape of the oscillatory process on the previous cable line and the stable repetition of the same curve, a suitable reflectogram was identified (Fig. 8). After analyzing the ICM results, it was concluded that the true ARM reflectogram is the one shown in Fig. 7(c), which was confirmed on-site using the acoustic fault location method. The difference in distance between the two methods on this cable line was 100 m. ARM showed the more accurate location of the fault. It should be noted that during the determination of the fault zone, the discharge voltage and transition resistance did not change.

On the third cable line (CL No. 3), ARM could not be applied. During the determination of the fault zone, the discharge voltage increased to 15 kV, and it was not possible to achieve stable arc burning at the fault location. In this situation, only the ICM method was applied, which almost immediately produced a form of oscillatory process that did not change during a series of discharges (Fig. 9).

Further on-site determination using the acoustic method confirmed the results of ICM. The discharge voltage and the value of the transition resistance did not change, and the discrepancy on site was no more than 7 m.

We should make an important note that the use of fault burning on these CL was not considered due to a prohibition on its application, which was caused by sections of the route passing through cable structures. Prior

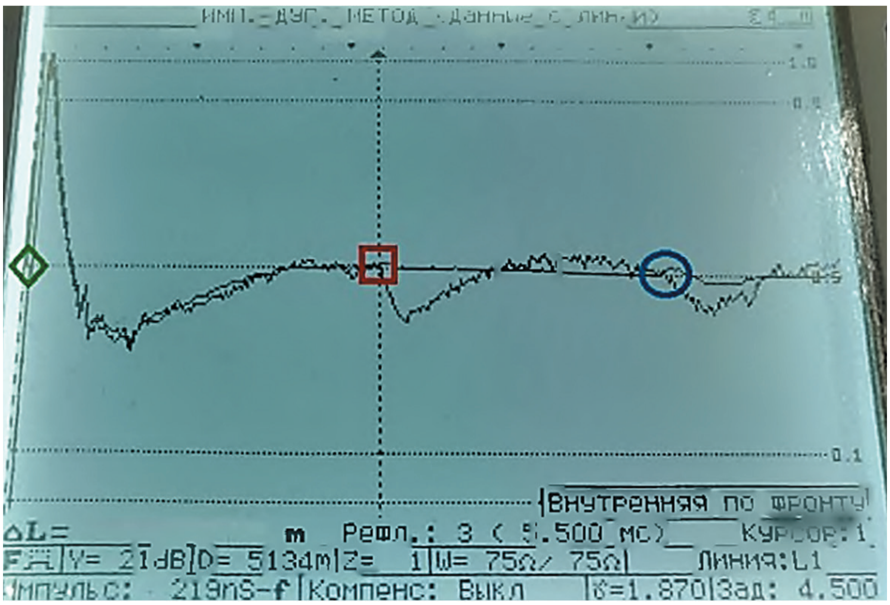
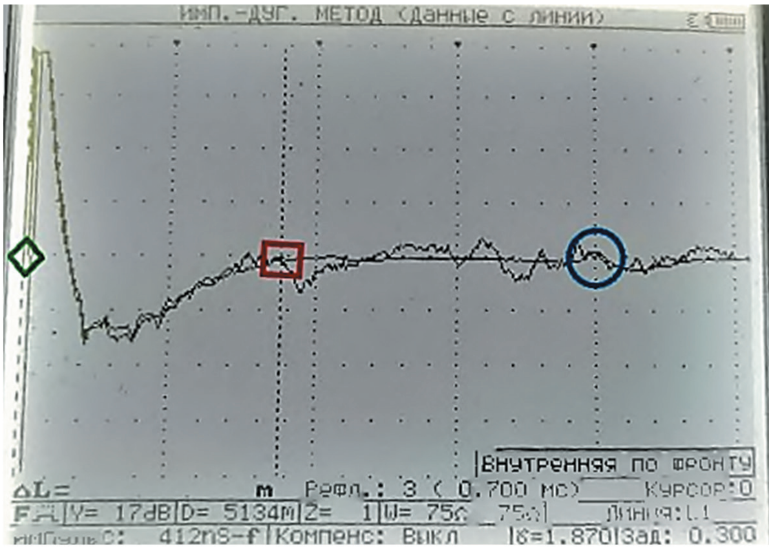


Fig. 6. *Repeated reflectogram when using ARM on CL No. 1*
Рис. 6. *Повторная рефлектограмма при использовании ARM на CL № 1*



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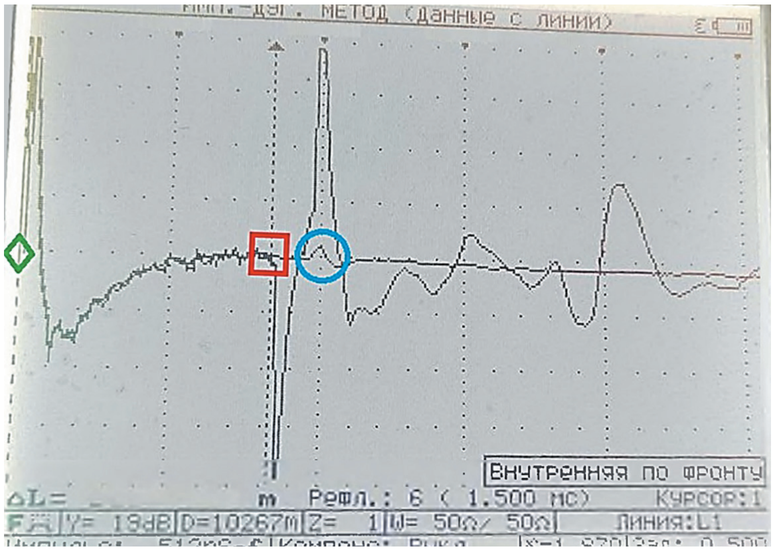

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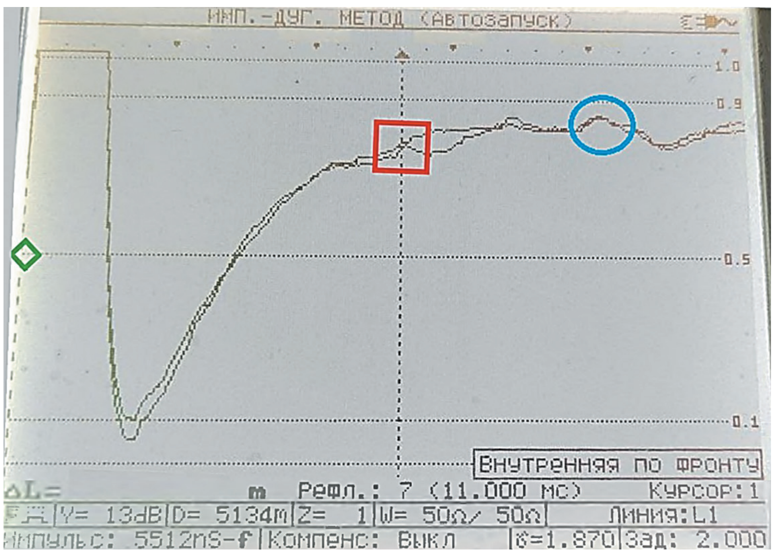

c

Fig. 7. *Reflectograms when using ARM on CL No. 2*
Рис. 7. *Рефлектограммы при использовании ARM на CL № 2*

Fig. 8. *Reflectogram when using ICM on CL No. 2*
Рис. 8. *Рефлектограмма при использовании ICM на CL №2*

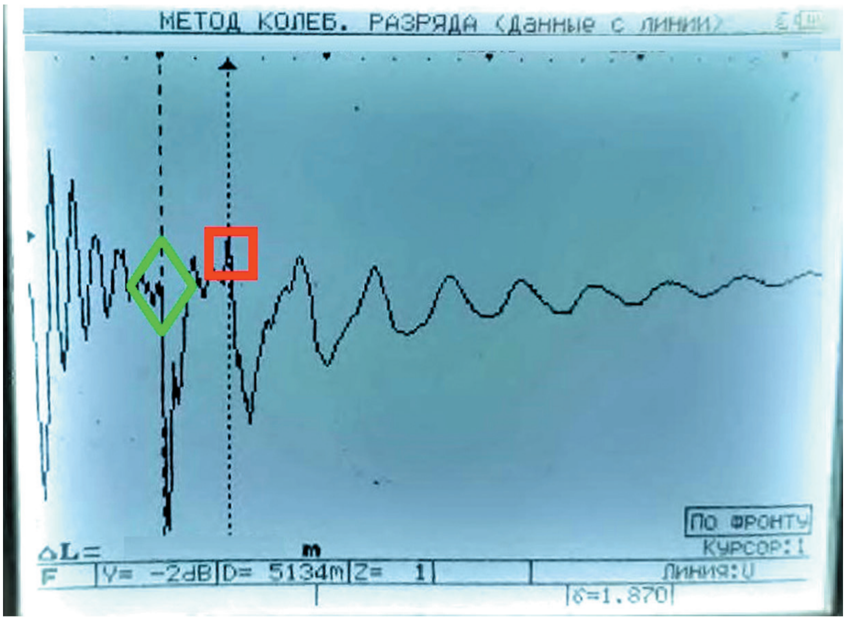

Fig. 9. *Reflectogram when using ICM on CL No. 3*
Рис. 9. *Рефлектограмма при использовании ICM на CL № 3*

to accurately identifying the fault zone, fault burning poses a high risk of fire if the fault is located within cable structures.

It should also be noted that the number of tests conducted were limited, and the results obtained are most applicable to this particular set and configuration of CLs. However, repeatable reflectometer traces were ensured for each CL, which still allows for the interpretation of results for other CLs as well.

CONCLUSION

The obtained results highlight specific challenges and complexities, as the captured reflectograms have a more complex appearance compared to those presented in operating manuals and literature. Moreover, it was revealed that the ARM method, which is positioned as the most effective, non-burning, and simple method for locating cable line faults, does not perform sufficiently well at high discharge voltages. Based on the experience of several electrotechnical laboratories in Moscow, it was found that this method has a discharge voltage limitation of 5–8 kV for arc ignition and obtaining readable reflectograms, which makes it poorly applicable to creeping discharges. In a situation where the vast majority of faults are single-phase short circuits exhibiting creeping discharge, this limitation poses a significant obstacle to ARM implementation[9] [17]. At the same time, ICM, previously considered difficult to use, is becoming more feasible with the advancement of semiconductor technology and it is a classical method used since the last century. Its main difficulty lies in the analysis of oscillograms and a large error in distance. Furthermore, its application is limited by transition resistance in the hundreds of kΩ. However, it was successfully implemented on the cable lines discussed above, where the resistance value reached tens of MΩ. The problem of distance error remains open and difficult to solve due to its operating principle. The most optimal way to solve these problems is a combination of the impulse current method and the impulse-arc method. Then, ICM serves as a marker of the fault zone for the ARM reflectogram, which in turn provides minimal on-site error.

It follows that the most optimal sequence of actions for efficiently determining the fault zone locating may be the following algorithm:

1. Insulation measurement with a megohmmeter to determine transition resistance and fault type. In case of creeping discharge, the megohmmeter may show normal insulation resistance; in such a case, it is recommended to check for fault using high-voltage tests.

2. Application of the TDR method to rule out CL breaks and faults with near-zero transition resistance.

3. Application of the ICM as a marker to estimate distance to the fault zone.

4. Application of the ARM to determine the fault zone with minimal error.

5. However, it must be understood that some methods may prove ineffective. In such a case, it is necessary to achieve greater consistancy of identical reflectograms using other methods. If no method yields satisfactory results, proceed with cable burning (fault conditioning).

6. After fault zone identification, it is necessary to establish its geographical reference using cable route maps. If unavailable, conduct route tracing, then precisely locate the fault onsite using any possible absolute method.

However, it should not be forgotten that each new fault in a CL has its own characteristics, precluding universal solutions for fault locating.

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