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RESEARCH ARTICLE

Assessment of an Overcurrent Protection Strategy Based on Thermal Stress Curves in Distribution Networks Under Reconfiguration Scenarios

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ABSTRACT Network reconfiguration enables the restoration of power supply in interrupted areas after faults or planned maintenance events. However, changes in network topology can often lead to alteration in the direction and magnitude of fault currents, undermining the coordination of overcurrent relays. In response to this challenge, adaptive protection systems have been developed that utilise system-wide communication to recalibrate relays dynamically. However, implementing system-wide communication comes with significant economic burdens, data integrity concerns and infrastructure limitations, especially in underdeveloped communities. In this study, the analysis of the overcurrent protection strategy based on thermal stress curves is conducted, to validate the appropriateness of the relay settings for a reconfigurable distribution network. The methodology was demonstrated on a test distribution system utilising directional overcurrent relays. The results demonstrate that the proposed protection strategy offers a simple and cost-effective means to enhance the effectiveness of power system protection within a reconfigurable grid. Consequently, this method presents an alternative to the concept of adaptive protection.

INDEX TERMS Distribution network reconfiguration, overcurrent relay, thermal stress curve.

I. INTRODUCTION

The electric power system is one of the most dynamic man-made systems created by humans, often undergoing multiple state changes. In the last 15 years, the distribution system has faced a thorough transformation from a passive to an active network after the inclusion of many new components and elements, like distributed generation (DG) and energy storage. These changes have made the operation, control and protection of the distribution grid a challenge [1]. Consequently, proper planning is required for its efficient and reliable operation in terms of restoration and relay coordination. The occurrence of the first fault in the network is referred to as the $N-1$ fault criterion. Branch circuit breakers (CB) are used to isolate this fault and restore the maximum unaffected part of the distribution network. This alters the network topology, and therefore the magnitude and direction of the fault currents detected by the various relays. In this scenario, the distribution network becomes susceptible to relay malfunctions or delays due to a potential impending fault [2].

Therefore, network reconfiguration has emerged as a key feature for the functionality of self-healing grids, with the main goal of restoration of power supply to prosumers. It affects the distribution grid by changing the states of normally open and normally closed switches, and, aside from its main goal, it may also be used to achieve various objectives, including, but not limited to, minimal power loss [3], [4], balanced load [5], high reliability [6], [7], [8] and uniform voltage profiles [9]. The aforementioned

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secondary goals can be achieved only with a fully automated grid, where switching elements, like CBs and/or disconnectors, are operated remotely. Researchers have proposed numerous solutions to optimise the network reconfiguration process [10], [11], [12], [13], [14]. However, as already stated, changes in the network's topology can lead to changes in power flow direction and fault magnitudes [15], [16], [17]. A novel approach coordinating DOCRs in response to the evolving transient network topology during short-circuit events was introduced in [18]. This method leveraged the dynamic model of overcurrent relays and employed linear programming techniques for effective coordination. Finally, it can be stated that there is an urgent need to re-evaluate power system protection strategies to protect utilities.

In general, grid reconfiguration and relay coordination are two different and often conflicting challenges. As said, the main goal of reconfiguration is to maximise load recovery so that the network remains radial, and to produce an optimal switching schedule if secondary goals are applied [19], [20], [21], [22], [23], [24]. In relay coordination, on the other hand, the goal is to minimise the relay operating time, based on the delay between the primary and backup relays, and to generate optimal relay settings [25], [26], [27], [28], [29]. Thus, reconfiguration maximises its objectives, but increases system vulnerability during potential impeding faults, while the relay optimisation minimises its objectives by scheduling relay settings to disconnect the faulted element from the network promptly, while ensuring proper coordination between the primary and backup relay pairs. The problem of relay miscoordination demands serious attention. The publication [30] highlights that relay failures, inaccurate settings and communication errors together contribute to over 60 % of faults in protection and control systems. In addition, the results of [31] show that 57 % of human-induced power failures are due to errors in the manufacture, installation, and maintenance of equipment, including inaccurate settings of protection relays.

Considering the aforementioned complexity, it is imperative to prevent inappropriate relay operation in various operating conditions. As the distribution system undergoes radical structural changes due to the rapid increase in demand and the integration of DG, the goal of this paper will be to simplify its protection strategy, whilst maintaining its efficiency.

DGs offer multiple benefits for power networks, such as: power loss reduction, voltage profile support, line and transformer congestion relief, investment deferral, etc. [32]. However, DGs also introduce new challenges to network protection philosophy, such as possible overvoltage violations [33], the increase of fault currents, bidirectional power flows [34], [35], [36] and its variations due to maximum/minimum load conditions and maximum/minimum renewable energy generation intermittency. These challenges cause new problems for the overcurrent relay (OCR) protection, which may eventually malfunction as a result of numerous power operating conditions [37], [38], [39]. Efforts to address these challenges have been made in studies such as [40] and [41], which attempted to incorporate the settings of OCRs as constraints in the network reconfiguration optimisation problem. The research presented in [42] provided a comprehensive discussion on the emerging concept of Inverter-Based Distributed Energy Resources (IBDERs) and their profound impacts on the studies of protection, control, operation, and planning in distribution networks and microgrids (MGs). Furthermore, the research in [43] introduced optimal deployment strategies for dual-setting DOCR in multiple source meshed distribution networks. It employed the augmented $\epsilon-$constraint method to balance relay operation time and the number of dual-setting DOCR deployments.

Adaptive protection has proven to be a promising strategy for increasing reliability and meeting safety requirements. It involves the integration of power system communication, control and monitoring technologies. Adaptive protection relies heavily on an extensive and reliable communication infrastructure and a centralised automation system to perform its core task of updating protection settings dynamically throughout the distribution network [44]. The main reason behind creating this concept is that the topology of the distribution network is not constant over time, and changes occur in the network resulting in different configurations. This simply means that the protection relays need to be updated according to the network configuration to cope with the now changed circumstances. By using adaptive protection, these relays are not readjusted manually, but their settings are updated dynamically via a central Supervisory Control and Data Acquisition (SCADA) system.

However, developing a full communication infrastructure within the distribution network is costly and still relatively uncommon, even in more developed countries. Moreover, the core concept of adaptive protection involves updating its settings continuously in response to new network configurations. In practical terms, this would entail taking special care to build a resilient communication network, in order to protect the power grid and prosumers from intentional cyberattacks.

An alternative approach to adaptive protection is proposed in this article. Specifically, it builds upon previous research conducted by the authors in the optimisation of OCRs' operation in power distribution networks [45]. The referenced article introduced a novel method for optimising and coordinating directional overcurrent relays (DOCRs), taking into account thermal equivalent short-circuit currents. Its aim was to address and clarify misconceptions in this research area.

Continuing from the previous research, the analysis will be carried out for previously optimised OCRs during network reconfiguration. Due to the reason that the once-established protection settings for the original configuration may be rendered useless for other configurations, the contribution of this paper is demonstrating that the proposed novel aproach presented in [45] is not just optimal for original configuration, but also effective against other configurations. This is backed in this article by simulation results, which demonstrate that the risk of thermal damage and/or destruction of the protected elements is negligible, even in different configurations, albeit in those circumstances relays are not set optimally.

Thus, the proposed protection strategy is a viable and much less financially burdening alternative to adaptive protection. Its main strength lies in the fact that, at least in the forseeable near future, reconfiguring a network will be done for faults or planned maintenance reasons, and not to accomplish secondary goals (dynamic minimisation of power losses, voltage deviation, etc.). This simply means that a new network configuration will be used for a relatively short time while the fault is cleared, the element repaired, or maintenance carried out, and will then revert to the original configuration. During this time, it is not necessary to optimise relay settings, but only to ensure that the relays, which are set optimally for the original configuration, will not operate too slowly or fail to operate, thus inadvertently causing thermal damage and/or destruction of the protected elements.

This article is divided into the following Sections: Section I introduces the network reconfiguration concept, while section II will provide an overview of the previous research on the topic of adaptive protection. Section III will define the proposed OCR optimisation problem statement, and Section IV will conduct the analysis for the network under reconfiguration, demonstrating the hypothesis with simulation results. Additionally, Section V will present a Discussion and Conclusion on the scientific contributions of this paper.

II. ADAPTIVE PROTECTION LITERATURE OVERVIEW

Ensuring the reliable operation of the distribution network mandates its reconfiguration after certain events. Altering the network's topology in this way may decrease the sensitivity of the relays, ultimately resulting in their malfunction and leading to a degradation in the performance of the protection system. Therefore, many researchers argue that adaptive settings of the relays are necessary for the restructured distribution network. To integrate adaptive protection into a SCADA distribution management system (DMS), the open/closed states of all switch-disconnectors and CBs must be updated in real-time, and the distribution network model in SCADA/DMS must reflect the current network topology accurately. If the network initially includes OCRs and CBs only at the beginning of each feeder (a well-established protection strategy for passive grids), adjusting the protection parameters will be much simpler compared to situations where protective devices are scattered throughout various nodes of the distribution network (protection ''in depth'', distinctive for active grids) [44]. In the latter case, ensuring the selectivity of protective devices becomes a major challenge. Nowadays, with the inclusion of new elements like DGs, a battery energy storage system (BESS), Static Synchronous Compensators (D-STATCOMs), etc., in distribution networks, this task becomes even more complex.

Therefore, several overcurrent adaptive protection schemes have been developed to address these challenges. In [46], a method for robust protection coordination settings of directional overcurrent relays, considering $N-1$ contingencies, was proposed and the impact of change in tap positions of on-load tap changers has also been considered. Based on the detailed investigations on the IEEE 14-bus test system, the authors drawn the conclusion where they stated that the solution of the formulated problem would provide the settings of the DOCRs which will be valid for all the $N-1$ topologies created after outage of any single line, transformer or a generator. In [47], a new scheme of recloser-fuse coordination for reconfigurable radial distribution networks considering DGs is introduced. Further, a new graph theory based approach has been developed to obtain all possible configurations of any radial network. Also, an efficient constraint reduction strategy has been introduced to reduce the number of effective constraints in the formulated optimization problem. Authors concluded that the presented protection scheme can be used in distribution automation system to ensure secure and efficient operation of the distribution network. In [48], a proposal has emerged to adapt for prolonged service continuity in radial lines during overloading conditions by adjusting the technical and climate circumstances. Reference [49] introduces a concept to achieve optimal coordination using linear programming under the principle of adaptive overcurrent protection. This idea entails conducting load flow studies, optimising relay settings, and transmitting the new settings to relays, utilising SCADA to monitor the network. Another adaptive overcurrent protection scheme is reported in [50], aiming to mitigate the effects of DG penetration partially. An adaptive overcurrent protection scheme for grid-connected and islanded mode operation is presented in [51]. Similarly, [52] proposes an adaptive overcurrent protection scheme that adjusts relay settings for peak and off-peak network conditions. The proposals in [53], [54] focused primarily on identifying islanding or grid-connected operations, including DGs in radial networks. In [55], [56], [57] the authors concentrated primarily on switching setting groups for OCRs on the present radial or meshed network, considering DGs. Other adaptive overcurrent schemes without using optimisation algorithms are presented in [58], [59], [60], where protective devices are reset based on lookup tables, multi-agent systems and fundamental electrical circuit calculations. Studies in [61], [62], [63], [64] proposed adaptive overcurrent coordination with DGs for meshed networks employing Fuzzy Logic, a Genetic Algorithm, a Neural Network, Ant Colony Optimization, Interior Point Method, and Differential Evolution. Additionally, a separate line of research has focused on the development of adaptive protection schemes for OCR coordination within reconfigurable microgrids' featuring [65], [66], [67].

Continuing with adaptive protection, its utilisation specifically for optimising OCR also presents various challenges. These methodologies typically rely on the presence of communication systems that enable remote coordination of OCR settings through a central control unit. However, it is important to acknowledge that deploying communication systems involves significant costs, particularly within distribution networks. The high number of line sections and relays compared to transmission networks means that such solutions are impractical economically [30]. These issues can potentially result in incorrect information being transmitted to the central control unit. If the information about the new network topology is inaccurate, there is a risk that the updated relay protection settings will be incorrect as well. Consequently, changes in relay settings, which are necessary in response to variations in the power system topology, may lead to malfunction of the protection system.

Furthermore, it's important to consider the possibility of influencing relay protection settings via the internet. Communication systems are vulnerable to cybersecurity threats and bugs. For instance, research studies [68], [69], [70] have explored the consequences of communication failures within microgrids, and have demonstrated that even minor interruptions in communication can lead to significant damage to the physical system. Additionally, it's worth noting that existing SCADA systems may lack the necessary capabilities to enable active network management of distribution grids [30].

Additionally, the fundamental concept of minimising inverse-time OCRs is complicated by a combinatorial explosion. This arises because relay parameters become volatile over time due to changes in network topologies. Essentially, each OCR will have n Time Multiplier Setting (TMS) and Plug Multiplier Setting (PMS) parameters, corresponding to n different network configurations. In this vast solution space, finding an optimal solution, i.e., the minimum overall total relay operating time (a sum of all individual relays' operating times), becomes challenging. Enhancing existing methods and heuristic algorithms, along with proper detection and avoidance of infeasible solution regions, will require significant effort to translate theoretical knowledge into practical network protection strategies. Particular attention must be paid to avoid situations where the overall total relay operating time for the observed network is minimised, but an individual relay causes damage to its protected element due to its associated operating time exceeding the thermal equivalent short-circuit current.

Although the implementation of adaptive protection philosophy is currently not feasible for most Distribution Network Operators (DNOs) due to the high costs associated with building and installing the communication infrastructure, it is, however, anticipated that this issue will be resolved in the future. Once resolved, there will be no obstacle to incorporating adaptive protection into real distribution networks. For the moment, even if the funds were not a problem, only definite-time OCRs can be used for adaptive protection (due to their simplicity), but then the optimisation cannot be performed (since t-I function is actually a constant). It is essential to highlight that the protection philosophy for reconfigured distribution networks can still be achieved, even without minimising relay operation time, as long as this potentially prolonged time does not result in degradation or damage to the protected element.

III. OVERCURRENT RELAY OPTIMISATION METHODOLOGY

An OCR is a protective device designed to activate or "pick up" when the measured current exceeds a predefined treshold or setting. Its input component is typically a current measuring transformer (CT), and its output component is a CB, which will open its contacts upon receiving the tripping signal. In distribution systems, OCR coordination relies on primary and backup protection [26]. Both primary and backup relays are responsible for detecting and sensing faults as soon as they occur, but only the primary relay should operate, leaving the backup relay operation as a contingency measure.

A. INVERSE TYPLE OCR PARAMETERS

The goal of the OCR coordination optimisation problem is to minimise the total sum of primary relays' operation times across the network, while also maintaining consistent coordination time intervals between all primary and backup (P/B) relay pairs. Specifically, this entails determining the appropriate TMS and PMS for each inverse OCR [26]. In this paper, the response time of the observed OCR is represented with the nonlinear and well-known Inverse Definite Minimum Time (IDMT) characteristic curve, based on the IEC Standard [71], which is expressed in the following equation:

$$t_i = \left(\frac{\alpha}{{PMS_\mathrm{i}}^{\beta} - 1} + L \right) \cdot TMS_\mathrm{i}. \tag{1}$$

Here, the constants α, β, L define the characteristics of the selected relay type, and their values are given in [72]. TMS_i is the time multiplier setting of relay R_i. In practice, the values of TMS are set in the range between 0.05 – 1.2 [72]. PMS_i is the plug multiplier setting of relay R_i. It is the current parameter of OCR, and it depends on the ratio between the actual fault current and the calculated pickup current, as given in the following equation:

$$PMS = \frac{I_\mathrm{SC}}{PS}. \tag{2}$$

Here, I_SC is the actual short-circuit current flowing through the relay (via CT) for faults of the protected line, and PS is the plug setting (pickup current). In practical cases, PMS is usually set based on the line current carrying capacity, and the latter is predetermined in the planning stage of the distribution network expansion by solving load flow equations. In this article, the authors consider an example of a meshed distribution network where the lines have a predefined maximum load current value (carrying capacity or ampacity) associated with their cross-section. Therefore, the PS is considered as a constant value for each line, which is calculated by multiplying the maximum load current of each line by factor 1.2.

B. COORDINATION CONSTRAINTS

As short-circuit currents need to be detected accurately by both the primary and backup relays, the latter should only trip if the primary relay fails to operate within a predefined period known as the coordination time interval (CTI). Therefore, the loss of coordination between P/B relay pairs will be indicated if the CTI is not adhered to. The CTI represents the operating time of the CB, measured from the moment the CB receives a trip signal from the relay until its contacts open and prevent the flow of fault current.

$$t_{\mathrm{j\_b}} - t_{\mathrm{i\_p}} \geq CTI. \tag{3}$$

In (3), $t_{\mathrm{j\_b}}$ and $t_{\mathrm{i\_p}}$ are the operating times of the backup relay j and the primary relay i, respectively. CTI is usually set in a predefined range of values between 0.2 and 0.5 seconds [72]. In this paper, it was set to 0.3 s, meaning that the employed protection devices are numerical relays.

The coordination constraint mentioned above can be reformulated in terms of discrimination time as follows:

$$\Delta t_{\mathrm{ij}} = t_{\mathrm{j\_b}} - t_{\mathrm{i\_p}} - CTI. \tag{4}$$

Here, Δt_{ij} represents the discrimination time of a P/B relay pair. If Δt_{ij} is a negative value, it will result in the miscoordination of the primary and backup relays, leading to an infeasible solution to the original optimization problem. In practical terms, this means that both relays have operated for the same fault, causing a larger portion of the network to be shut down unnecessarily, resulting in power cuts for some consumers. However, if Δt_{ij} is a positive value, the solution is feasible, as there is no miscoordination between the primary and backup relays. It is important to note that a negative Δt_{ij} will not cause damage to the protected element if the upper time limit $t_{\mathrm{i,max}}$ (defined in the following subsection) of a backup relay is kept below the thermal stress curve. Thus, for a reconfigured network, maintaining Δt_{ij} as positive will be desirable, but not essential or mandatory.

C. OPERATING TIME LIMITS

The OCR operating time must be within a reasonable range of values that will not cause damage to the protected element. The relay requires a minimum time to initiate the trip mechanism of the corresponding CB, and it is essential to avoid its too long activation time when a fault occurs. The operating time constraint is shown in the following equation:

$$t_{\mathrm{i,min}} \leq t_{\mathrm{i}} \leq t_{\mathrm{i,max}}. \tag{5}$$

Here, $t_{\mathrm{i,min}}$ and $t_{\mathrm{i,max}}$ are the minimum and maximum operating times of a relay R_{i}, defined in accordance with the requirements of the protective schemes.

In [45], it was highlighted that a thermal equivalent short-circuit current is critical for the proper rating of power conductors and equipment (lines, busbars, etc.), with special

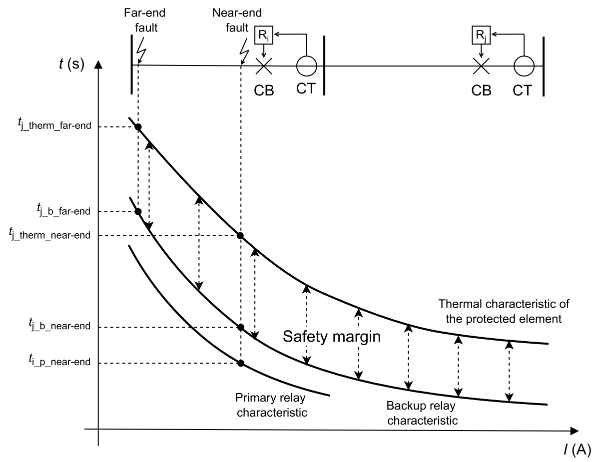

FIGURE 1. On the explanation of safety margin.

emphasis on an element's cross-section calculation and determination. It was stated that, depending on the occurrence and the type of faults at the beginning and the end of the protected elements, even a long t_{i} associated with lower values of fault currents can cause damage to an element if the thermal stress curve is reached. Therefore, operating time limits were studied thoroughly. Because for numerical relays, the trip signal can be generated in 30 ms after detecting that the current has overshot its threshold value, $t_{\mathrm{i,min}}$ was considered equal to that value. In [45], the authors stated that the parameter $t_{\mathrm{i,max}}$ should be associated with the thermal equivalent short-circuit current of the protected element through the following general equation:

$$I_{\mathrm{SC}} \leq \frac{I_{\mathrm{SC\_therm}}}{\sqrt{t_{\mathrm{i}}}}. \tag{6}$$

Here, I_{SC} is the actual short-circuit current flowing through the element, t_{i} is the relay operating time, and $I_{\mathrm{SC\_therm}}$ represents the thermal equivalent short-circuit current, which can be found in the electrical design documentation of cables and overhead lines. When the actual short-circuit current flowing through the element for a time duration t_{i} is greater than $I_{\mathrm{SC\_therm}}$, the generated heat will begin to melt the copper or aluminum wires, degrading its mechanical and electrical (insulation) parameters. In [45], the authors performed the above inspection for the worst-case scenario, where a backup relay operating time was observed, which must be lower than the time necessary to reach the thermal stress curve. The latter will be denoted as $t_{\mathrm{j\_therm}}$, where j is the backup relay of the primary relay i. The reason why only a backup relay was observed concerns the fact that its operating time must be longer than the primary relay's, i.e., the coordination constraint must be satisfied for each P/B pair. Additionally, this check was performed for the beginning and the end of the protected element because the thermal stress curve of the protected element does not have equal parameters as the IDMT curve used for OCRs. In other words, it is not enough to observe only the beginning of the line since the intersection of both curves may occur anywhere else along the line. For this reason, the backup relay operating time was inspected for both the beginning and the end of the protected element.

Thus, in terms of different fault locations, (6) can be rewritten as follows:

$$t_{\text{j\_b\_near\_end}} \leq t_{\text{j\_therm\_near\_end}} = \left(\frac{I_{\text{SC\_therm}}}{I_{\text{SC\_near\_end}}}\right)^2, \quad (7)$$

$$t_{\text{j\_b\_far\_end}} \leq t_{\text{j\_therm\_far\_end}} = \left(\frac{I_{\text{SC\_therm}}}{I_{\text{SC\_far\_end}}}\right)^2. \quad (8)$$

The concept of safety margin is introduced in order to maintain the time distance between the backup relay characteristic and the thermal curve of the protected element. The safety margin is the time distance that is sought to be maximised to ensure that no damage occurs to the protected element, as illustrated in Fig. 1. If this parameter is maximised during the OCR optimisation of the original configuration, it will imply a much greater probability that the optimised relay settings can remain unchanged for other configurations, and still not cause damage to the protected element (albeit the primary and backup relay operating times may be prolonged in those cases, due to different amounts of short-circuit currents). This is precisely the idea behind the analysis that will be performed in the subsequent Section.

D. OCR OBJECTIVE FUNCTION AND THE DEVELOPED OPTIMISATION ALGORITHM

The objective function (OF) presented in [45] is given in the following equation:

$$OF = \min \sum_{i=1}^{n} (W_i \cdot t_{\text{i\_p\_near\_end}} + \sum_{\substack{j=1 \\ j \neq i}}^{m} W_j \cdot \frac{1}{\Delta t_{\text{j\_therm}}}). \quad (9)$$

With the following parameters explained further:

$$\Delta t_{\text{j\_therm}} = \Delta t_{\text{j\_therm\_near\_end}} + \Delta t_{\text{j\_therm\_far\_end}}, \quad (10)$$

$$\Delta t_{\text{j\_therm\_near\_end}} = t_{\text{j\_therm\_near\_end}} - t_{\text{j\_b\_near\_end}}, \quad (11)$$

$$\Delta t_{\text{j\_therm\_far\_end}} = t_{\text{j\_therm\_far\_end}} - t_{\text{j\_b\_far\_end}}. \quad (12)$$

Essentially, the objective function of the optimisation problem is defined as the sum of the operating times of all primary relays and the reciprocal sum of the safety margin check. This approach ensures that the operation of backup relays occurs as far as possible from the thermal stress curve of the protected element [45].

Based on [73], the authors stated firmly that the coordination constraints should only be calculated at the beginning of the protected element (line). This is because the time delay Δt_{bp} between any primary and backup relay increases with line length, so it can be stated that coordination constraints between the P/B relay pairs should only be checked at the beginning of each line [45]. One notable exception is when using different types of inverse OCRs (standard inverse, very inverse, and extremely inverse) in the same network. In that case, coordination constraints should be checked for both the beginning and the end of the protected element; however, in this manuscript, that will not be the case. The first part of the modified *OF* remained the same as the standard objective function presented in many previous research papers, where only the operating time of a primary relay is considered, $t_{\text{i\_p\_near\_end}}$. Also, only the fault at the beginning of the protected element is taken into consideration, due to the fact that all the relays in the observed network are uniform [73], as mentioned previously. On the other hand, the second part of the OF represents the maximisation of the aforementioned safety margin between the backup relay operating time and the thermal stress curve for the beginning and the end

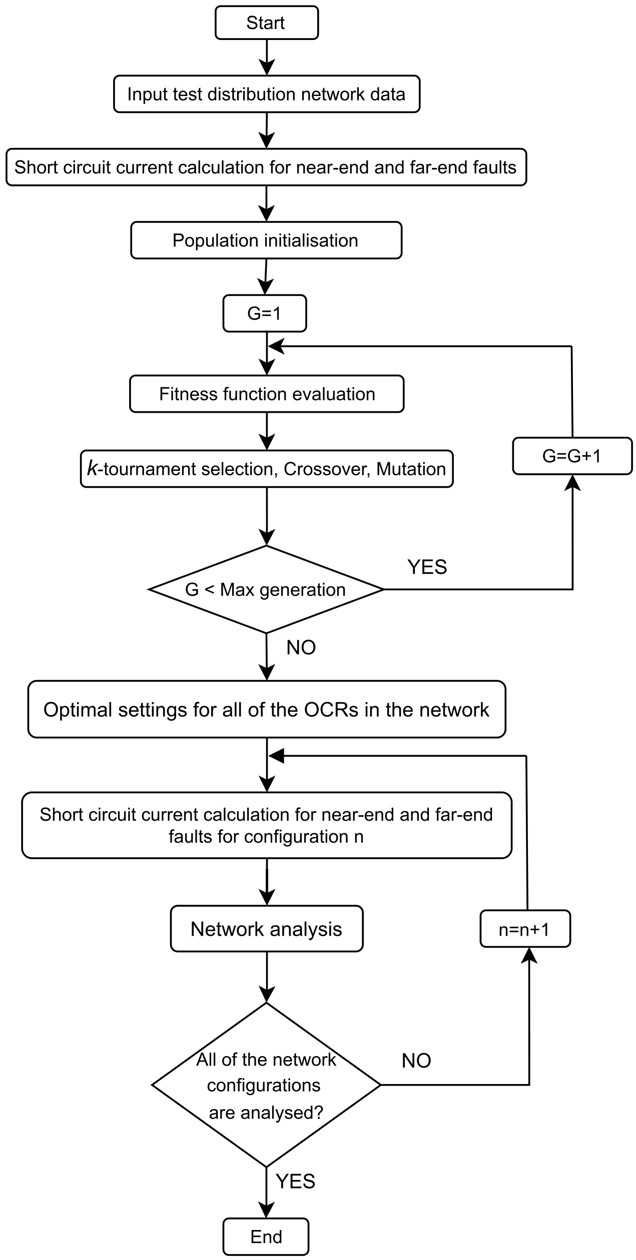

FIGURE 2. The flowchart of the Genetic Algorithm coupled with the analysis.

of the protection zone (line). By expanding the OF, the authors widened the safety margin between the backup relay operating curves and the thermal curves. Since minimisation and maximisation are opposed to each other, the second part was taken as a reciprocal value. The n represents the total number of primary relays in the network, while m represents the total number of backup relays for the primary relay *i* under consideration. W_i and W_j are the weights assigned to each part of the *OF*, respectively. Δt_{j_therm} is defined in (10), and represents the sum of the mentioned distances between the operating times of backup relays and thermal stress curves calculated in (11) and (12) for the beginning and the end of the protected zone (element).

A modified genetic algorithm was employed to minimise the operating times of primary relays simultaneously while maximising the time delay between the operation of the backup relays and their respective protected elements' thermal stress curves. The algorithm was modified in a way where individuals in a population were encoded into chromosomes using float number values, with each chromosome representing TMS values for primary protection relays. Afterwards, the optimisation algorithm employed k-tournament selection, single-point crossover and mutation until reaching the user-specified number of generations. With the obtained set of optimally chosen TMS values of all the relays in the network, the analysis was conducted for every configuration, with the goal to observe the breach of coordination constraints per each P/B relay pair, and, more importantly, the breach of the protected elements' thermal stress curves. It is important to mention that for the protection of other equipment in the distribution power system, aside from power lines or cables, a different approach would be necessary to tackle the optimization problem properly. This is because overcurrent protection alone is not sufficient for protecting all types of equipment.

The flowchart of the modified Genetic Algorithm, along with the analysis used in this article, is presented in Fig. 2.

IV. ANALYSIS OF OCR OPTIMISED SETTINGS UNDER NETWORK RECONFIGURATION

The complex topologies of distribution power networks and their associated changes that can be expected due to planned or unforeseen events increase the need for properly configured relay protection. OCRs must function correctly in the event of a reconfiguration of the distribution network. In other words, relay settings should be set to such values that will protect the associated element adequately for all configurations. The optimality criterion should be relevant only for the originalconfiguration, but, for others, due to their relatively short duration, only a possible breach of the thermal stress curve should be inspected.

In general, distribution networks are constructed as looped networks, especially in densely populated urban areas. However, due to their high complexity and easier management, they operate in a radial manner, meaning that distribution networks are divided into subsystems of radial networks containing open and closed tie-switches in normal operation. Determining the optimal topology via automated switching involves installing a communication infrastructure and manipulation equipment at predefined locations. Manipulation equipment may consist of CBs and load break switches, which can be controlled remotely or locally to achieve the optimal distribution network topology.

In this Section the analysis of OCR protection will be conducted, with the goal to prove that only one correct and optimal adjustment of relay parameters is necessary in order to protect the existing network successfully, which is prone to reconfiguration. By observing all configurations of the distribution network systematically, the analysis will provide insights into the robustness and reliability of the proposed overcurrent protection strategy based on thermal stress curves of the protected elements. The analysis was conducted for all configurations of the distribution network. In order to keep the article within the reasonable number of pages, three characteristic cases were chosen and will be presented in this Section.

The network under consideration where the analysis will be carried out is a medium voltage (MV) 20 kV grid under meshed operation which was already introduced in [45], and is presented in Fig. 3. As said, looped operation of two feeders is not yet common in European practice, but can, nevertheless, be technically achievable and feasible, if the DOCRs are used. It is expected in the near future that looped MV networks will become a widespread standard, in order to improve the Distribution System Operator (DSO) reliability indices, like SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), CAIDI (Customer Average Interruption Duration Index), etc.

The developed methodology is applicable to any closed loop and radial distribution network. This includes the presented test network and more complex network topologies. To avoid potential problems associated with high equalising currents, interconnected grids fed from 2 or more HV/MV substations are excluded from the analysis.

The following discussion will consider a ring-loop distribution network with an included DG unit, where all the switching elements (CBs) are closed, which will transition from meshed to radial operation after certain lines are disconnected. This means that, in a portion of the newly configured network, only unidirectional short-circuit currents may occur, and, as a result, certain directional relays will now not operate. Therefore, the looped ring network will transition to radial, due to, for example, a fault or planned maintenance on a network element. The goal here is to examine whether the relay protection (especially for backup relays) set with the TMS settings obtained for the initial (original) network configuration in [45], will react below the thermal stress curves of the protected lines for all other configurations. As said, optimality and reaction speed will not be of concern when observing other configurations, only the efficiency of the pre-set relays. Thus, an alternative will be tested

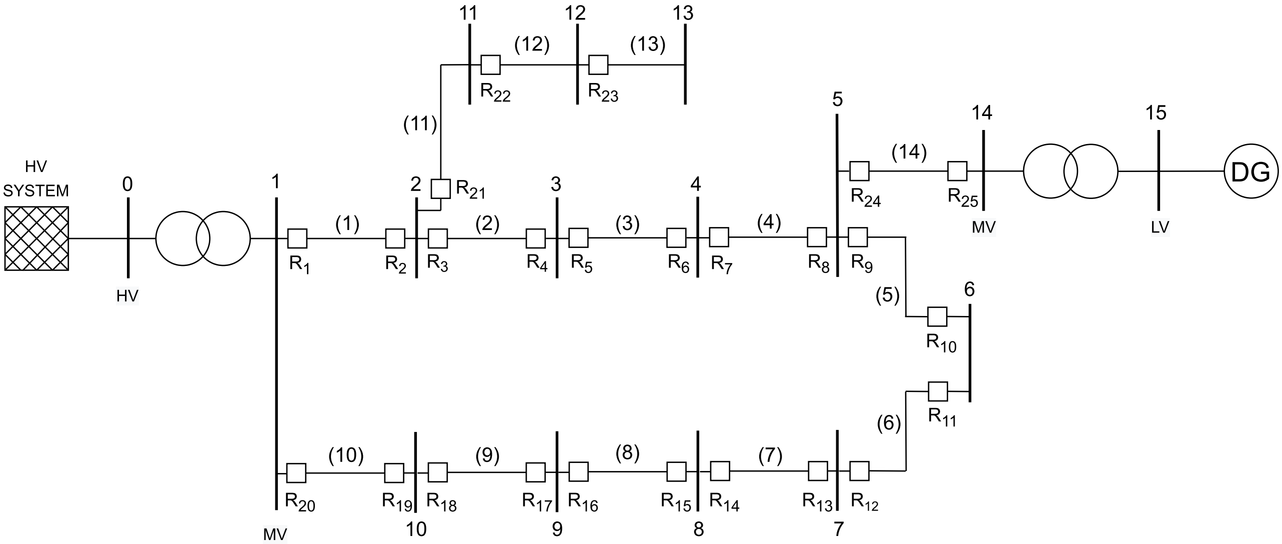

FIGURE 3. The single line diagram of a 16-bus MV distribution ring network [45].

TABLE 1. Short circuit currents in the new configuration with line (1) disconnected.

Relay pairs P/B	Near-end fault $I_{f\_near\_end}$ [kA]	Far-end fault $I_{f\_far\_end}$ [kA]
R_4/R_6	6.493/6.4493	6.0337/6.0337
R_6/R_8	6.9884/6.9884	6.4493/6.4493
R_8/R_{10}	7.4368/4.6170	6.9884/4.3496
R_8/R_{25}	7.4368/2.8216	6.9884/2.6388
R_9/R_{25}	2.8216/2.8216	2.7666/2.7666
R_{10}/R_{12}	4.8081/4.8081	4.6170/4.6170
R_{11}/R_9	2.7666/2.7666	2.7179/2.7179
R_{12}/R_{14}	4.9849/4.9849	4.8081/4.8081
R_{13}/R_{11}	2.7179/2.7179	2.6413/2.6413
R_{14}/R_{16}	5.2816/5.2816	4.9849/4.9849
R_{15}/R_{13}	2.6413/2.6413	2.5882/2.5882
R_{16}/R_{18}	5.4973/5.4973	5.2816/5.2816
R_{17}/R_{15}	2.5882/2.5882	2.5279/2.5279
R_{18}/R_{20}	2.8510/2.8510	5.4973/5.4973
R_{19}/R_{17}	2.5279/2.5279	5.2264/5.2264
R_{20}/-	8.1151/-	2.8510/-
R_{21}/R_4	6.1337/6.0337	5.6041/5.6041
R_{22}/R_{21}	5.6041/5.6041	5.4033/5.4033
R_{23}/R_{22}	5.4033/5.4033	5.2536/5.2536
R_{24}/R_{10}	4.6170/4.6170	4.9754/4.9754
R_{25}/-	7.1825/-	2.8216/-

for adaptive protection, which always calculates optimal relay settings for all configurations (risking combinatorial explosion), regardless of how short a time these new configurations will be operated for.

A. DISCONNECTED LINE (1)

For the case where line (1) is disconnected in the observed network, relays R_1, R_2, R_3, R_5, and R_7 become inactive. The remaining relays in the network have settings according to the defined values in [45], obtained after the optimisation of the original looped configuration. Due to the now changed topology of the observed network, the analysis requires the calculation of short-circuit currents for near and far-end faults, respectively. Therefore, Table 1 contains the results of the short-circuit analysis with line (1) disconnected.

Table 2 presents the results of the conducted analysis for the case of a short circuit occurring at the beginning of each protected line. Therefore, it examines whether the coordination constraint is satisfied for all pairs of P/B relay for this new network configuration, and, more importantly, whether the safety margin is satisfied for each protected line.

In the second and third columns of the Table 2, the operating times of the primary and backup relays are presented for near-end faults, calculated according to (1). In the fourth column of the Table 2 the coordination constraint is examined, according to (3). From the obtained results, it can be observed that the coordination constraint is not satisfied for all pairs of P/B relays. However, it is important to note once more that this network configuration is not permanent, meaning it usually lasts for a short period of time, until the planned maintenance is carried out or a previous fault, which occurred in line (1), is cleared. The correctness of the coordination criterion for all P/B relay pairs has already been tested and proven for the initial distribution network configuration in [45], which is considered as a permanent operational state.

Therefore, the authors' opinion is that a far more important step is to check whether the permissible thermal stress curve of each protected element has been breached during this short period (the duration of the new network configuration). Thus, any potential miscoordination which would result in a larger portion of the network to be disconnected than necessary, does not pose a significant problem. However, it is imperative to observe separately if the CTI is negative for each P/B pair, because, in that case, the operating time of a primary relay is going to be longer than that of a backup relay,

TABLE 2. The results of the conducted analysis for near-end faults in the new configuration with line (1) disconnected.

Relay pairs P/B	$t_{i\_p\_near\_end}$ [s]	$t_{j\_b\_near\_end}$ [s]	$t_b - t_p \geq CTI$	t_{therm} [s]	$\Delta t_{therm\_near\_end}$ [s]
R_4/R_6	0.635567	0.85595	$0.220383 < 0.3$	17.01291	16.15696
R_6/R_8	0.829864	1.082454	$0.252591 < 0.3$	14.48964	13.40718
R_8/R_{10}	1.057417	1.209449	$0.152032 < 0.3$	33.19277	31.98332
R_8/R_{25}	1.057417	2.432502	$1.375085 > 0.3$	88.84833	86.41582
R_9/R_{25}	2.008115	2.432502	$0.424387 > 0.3$	88.84833	86.41582
R_{10}/R_{12}	1.187918	1.458206	$0.270288 < 0.3$	30.60796	29.14975
R_{11}/R_9	1.598513	2.030758	$0.432245 > 0.3$	92.41553	90.38477
R_{12}/R_{14}	1.435399	1.708984	$0.273585 < 0.3$	28.47298	26.764
R_{13}/R_{11}	1.222737	1.615038	$0.392301 > 0.3$	95.77769	94.16265
R_{14}/R_{16}	1.667203	1.974296	$0.307093 > 0.3$	25.36101	23.38671
R_{15}/R_{13}	0.904518	1.243403	$0.338885 > 0.3$	101.444	100.2006
R_{16}/R_{18}	1.94154	2.254223	$0.312683 > 0.3$	23.40743	21.15321
R_{17}/R_{15}	0.589873	0.922467	$0.332594 > 0.3$	108.3881	107.4656
R_{18}/R_{20}	3.093886	3.672987	$0.579101 > 0.3$	147.2847	143.6118
R_{19}/R_{17}	0.232351	0.598217	$0.365866 > 0.3$	110.7157	110.1175
R_{21}/R_4	0.782914	0.85254	$0.069626 < 0.3$	76.86562	76.01308
R_{22}/R_{21}	0.469016	0.80573	$0.336714 > 0.3$	14.85632	14.05059
R_{23}/R_{22}	0.138461	0.481234	$0.342773 > 0.3$	16.90158	16.42035
R_{24}/R_{10}	0.151342	1.267482	$1.11614 > 0.3$	40.74894	39.48145

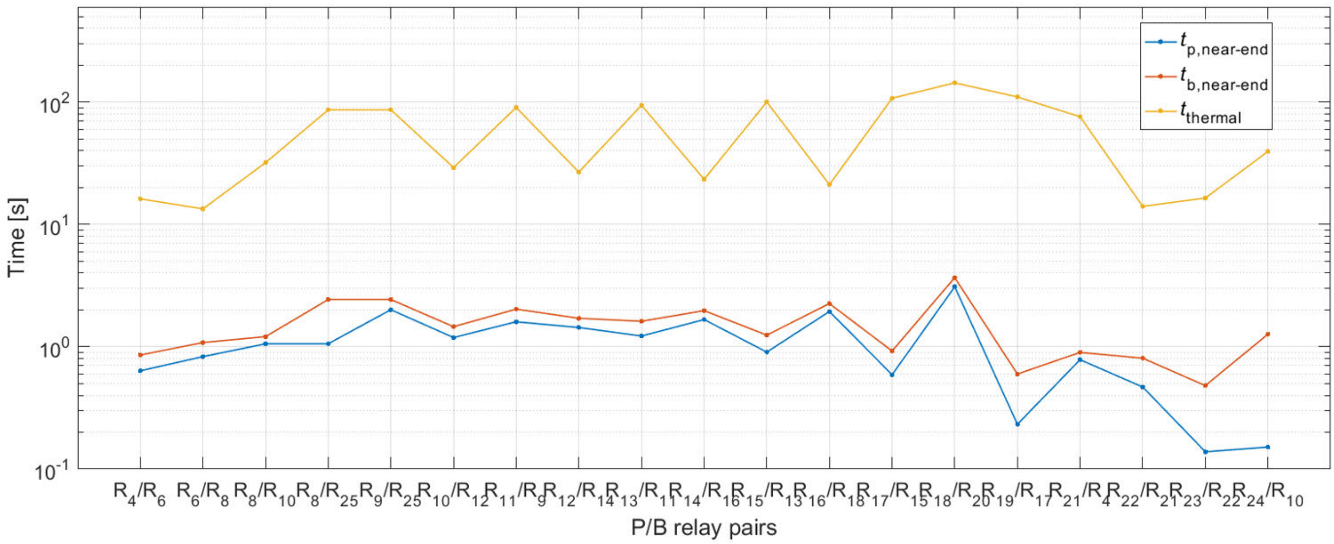

FIGURE 4. Graph of the results presented in Table 2 for near-end faults in the new configuration with line (1) disconnected.

meaning that the distance to a thermal stress curve should be inspected from the primary relay and not the backup one.

Therefore, in the fifth column of the Table 2, the elapsed time until thermal damage occurs to the protected line for the case of a near-end short circuit is calculated according to (7). In the sixth column of the Table 2, a check is performed to determine whether the safety margin is satisfied according to (11). That is, for example, in case of a fault on the line (3), primary relay R_6 should operate first in 0,829864 s, and if it malfunctions, his backup relay R_8 will operate in 1,082454 s. Since the coordination constraint is not satisfied, both relays will send a trip signal to their associated CBs, disconnecting both lines (3) and (4). However, a far more important fact than the miscoordination is that the operation of a backup relay R_8 has a 13,40718 s margin distance to the point of conductor melting time (thermal stress curve) for line (3), which will occur after 14,48964 s has elapsed.

From the results, it can be seen that the safety margin is satisfied for each pair of P/B relays. This means that all the lines are protected adequately from damage in case of a short circuit occurring at the beginning of each line.

The operating times of primary and backup relays for the case of near-end short circuit faults are shown in Fig. 4. The thermal curves are also depicted of the protected lines in the network. It is clearly visible from the figure that the safety margin is satisfied for each protected line.

The operating times of primary and backup relays for the case of near-end short circuit faults are shown in Fig. 4. The thermal curves are also depicted of the protected lines in the network. It is clearly visible from the figure that the safety margin is satisfied for each protected line. Also, another

TABLE 3. The results of the conducted analysis for far-end faults in the new configuration with line (1) disconnected.

Relay pairs P/B	$t_{\text{i\_p\_near\_end}}$ [s]	$t_{\text{j\_b\_near\_end}}$ [s]	$t_b - t_p \geq CTI$	t_{therm} [s]	$\Delta t_{\text{therm\_near\_end}}$ [s]
R_4/R_6	0.65254	0.878808	$\underline{0.226268 < 0.3}$	19.43357	18.55477
R_6/R_8	0.85595	1.116481	$\underline{0.260531 < 0.3}$	17.01291	15.89643
R_8/R_{10}	1.082454	1.209449	$\underline{0.216995 < 0.3}$	33.19277	31.98332
R_8/R_{25}	1.082454	1.949584	$0.86713 > 0.3$	37.20413	35.25454
R_9/R_{25}	2.030758	2.459931	$0.429173 > 0.3$	92.41553	89.9556
R_{10}/R_{12}	1.209449	1.484635	$\underline{0.275186 < 0.3}$	33.19277	31.70814
R_{11}/R_9	1.615038	2.051752	$0.436714 > 0.3$	95.77769	93.72594
R_{12}/R_{14}	1.458206	1.736138	$\underline{0.277932 < 0.3}$	30.60796	28.87182
R_{13}/R_{11}	1.243403	1.642335	$0.398932 > 0.3$	101.444	99.80169
R_{14}/R_{16}	1.708984	2.023773	$0.314789 > 0.3$	28.47298	26.44921
R_{15}/R_{13}	0.915427	1.258399	$0.342972 > 0.3$	105.6415	104.3831
R_{16}/R_{18}	1.973665	2.291694	$0.318029 > 0.3$	25.32264	23.03094
R_{17}/R_{15}	0.598217	0.928377	$0.33016 > 0.3$	110.7157	109.7873
R_{18}/R_{20}	2.254394	2.611461	$0.357067 > 0.3$	39.61875	37.00729
R_{19}/R_{17}	0.1565	0.415126	$\underline{0.258626 < 0.3}$	25.90744	25.49231
R_{21}/R_4	0.80573	0.980302	$\underline{0.174572 < 0.3}$	104.3473	103.367
R_{22}/R_{21}	0.475861	0.817488	$0.341627 > 0.3$	15.98224	15.16475
R_{23}/R_{22}	0.138461	0.481234	$0.342773 > 0.3$	16.90158	16.42035
R_{24}/R_{10}	0.146451	1.170356	$1.023905 > 0.3$	28.58756	27.41721

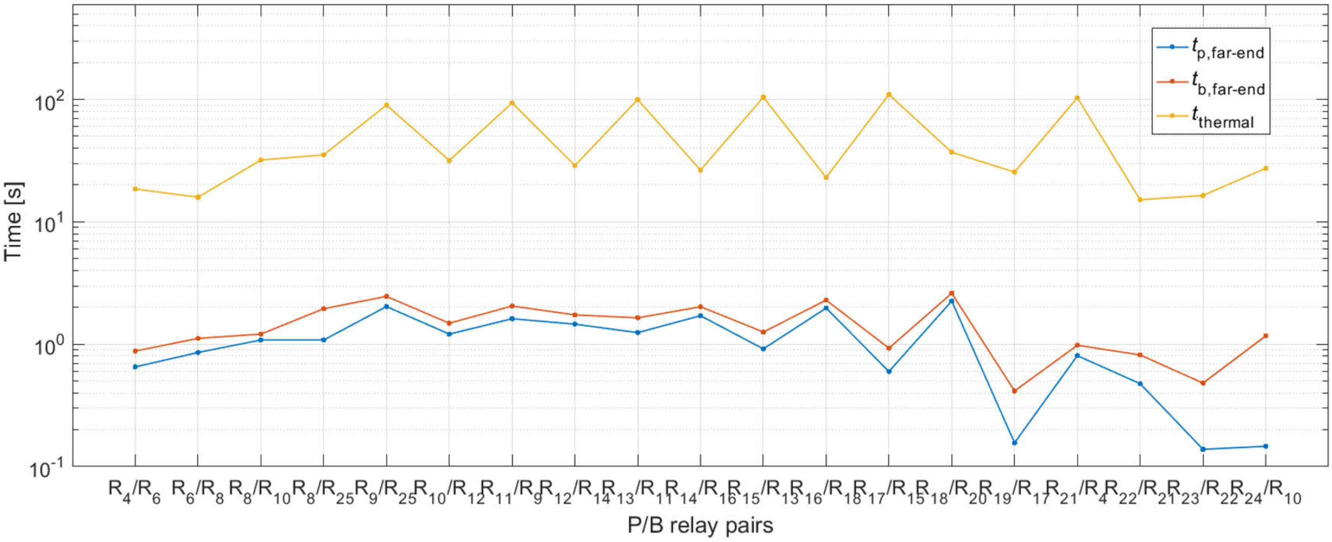

FIGURE 5. Graph of the results presented in Table 3 for far-end faults in the new configuration with line (1) disconnected.

interesting fact is that, albeit the coordination constraint is not satisfied for all P/B relays, still no backup relay operating time is lower than its associated primary relay operating time. In other words, CTI is always > 0, and only backup relays are paramount for the inspection of the safety margin.

Finally, another analysis must be carried out, and it concerns the far-end faults in the new configuration with line (1) disconnected. Thus, Table 3 presents the results of the conducted analysis for the case of a short circuit occurring at the end of each protected line.

In the fourth column of the Table 3, the coordination constraint is examined for the case of a far-end short circuit. Similar to the previous case of a near-end fault, it can be observed that the coordination constraint is not satisfied for the same pairs of P/B relays. Again, it is important to note that this network configuration is temporary, and it is more crucial to protect the line from damage due to thermal stress.

In the fifth column of the Table 3, the time elapsed until thermal damage to the protected line in case of a far-end short circuit is calculated according to (8). In the sixth column, the thermal discrimination time for each pair of P/B relays is shown, calculated according to (12). From the results, it can be concluded that, in this case as well, the safety margin is satisfied for each protected line.

Fig. 5 illustrates the operating times of the primary and backup relays for the case of a short circuit occurring at the end of each line. The thermal curves of the protected lines in the network are also depicted, positioned above the operating curve of the backup relays. This positioning indicates that the safety margin is satisfied, even in this scenario.

B. DISCONNECTED LINE (3)

Similarly to the case where line (1) was disconnected, in the occurrence of line (3) disconnection, relays R_2, R_4, R_5, R_6 and R_7 will become inactive. The remaining relays in the

TABLE 4. The summary results of the conducted analysis for the observed network with disconnected line (3).

Relay pairs P/B	Near-end fault			Far-end fault		
	$t_b - t_p \geq CTI$	t_{therm}	Δt_{therm}	$t_b - t_p \geq CTI$	t_{therm}	Δt_{therm}
R_3/R_1	0.260741 < 0.3	20.13403	18.18829	0.270365 < 0.3	23,08695	21,08821
R_8/R_{10}	0.152137 < 0.3	33.19277	31.98332	0.125815 < 0.3	33,19277	31,98332
R_8/R_{25}	1.37519 > 0.3	88.84833	86.41582	1.348868 > 0.3	88,84833	86,41582
R_9/R_{25}	0.424387 > 0.3	88.84833	86.41582	0.429173 > 0.3	92,41553	89,9556
R_{10}/R_{12}	0.270288 < 0.3	30.60796	29.14975	0.275186 < 0.3	33,19277	31,70814
R_{11}/R_9	0.432245 > 0.3	92.41553	90.38477	0.436714 > 0.3	95,77769	93,72594
R_{12}/R_{14}	0.273608 < 0.3	28.48441	26.77528	0.277932 < 0.3	30,60796	28,87182
R_{13}/R_{11}	0.392301 > 0.3	95.77769	94.16265	0.398932 > 0.3	101,444	99,80169
R_{14}/R_{16}	0.307093 > 0.3	25.36101	23.38671	0.314816 > 0.3	28,48441	26,46046
R_{15}/R_{13}	0.338885 > 0.3	101.444	100.2006	0.342972 > 0.3	105,6415	104,3831
R_{16}/R_{18}	0.312854 > 0.3	23.41595	21.16156	0.318157 > 0.3	25,37061	23,078
R_{17}/R_{15}	0.325554 > 0.3	105.6415	104.7261	0.33016 > 0.3	110,7157	109,7873
R_{18}/R_{20}	0.579101 > 0.3	147.2847	143.6118	0,357067 > 0,3	39,61875	37,00729
R_{19}/R_{17}	0.365866 > 0.3	110.7157	110.1175	0,258626 < 0,3	25,90744	25,49231
R_{21}/R_1	1.230257 > 0.3	20.13403	18.18829	1.269616 > 0.3	23,43714	21,43239
R_{22}/R_{21}	0.30721 > 0.3	9.133978	8.398847	0.311724 > 0.3	9,896916	9,150985
R_{23}/R_{22}	0.30926 > 0.3	9.894034	9.45985	0.312729 > 0.3	10,51231	10,07326
R_{24}/R_{10}	1.058107 > 0.3	33.19277	31.98332	1.085772 > 0.3	37,20413	35,96305

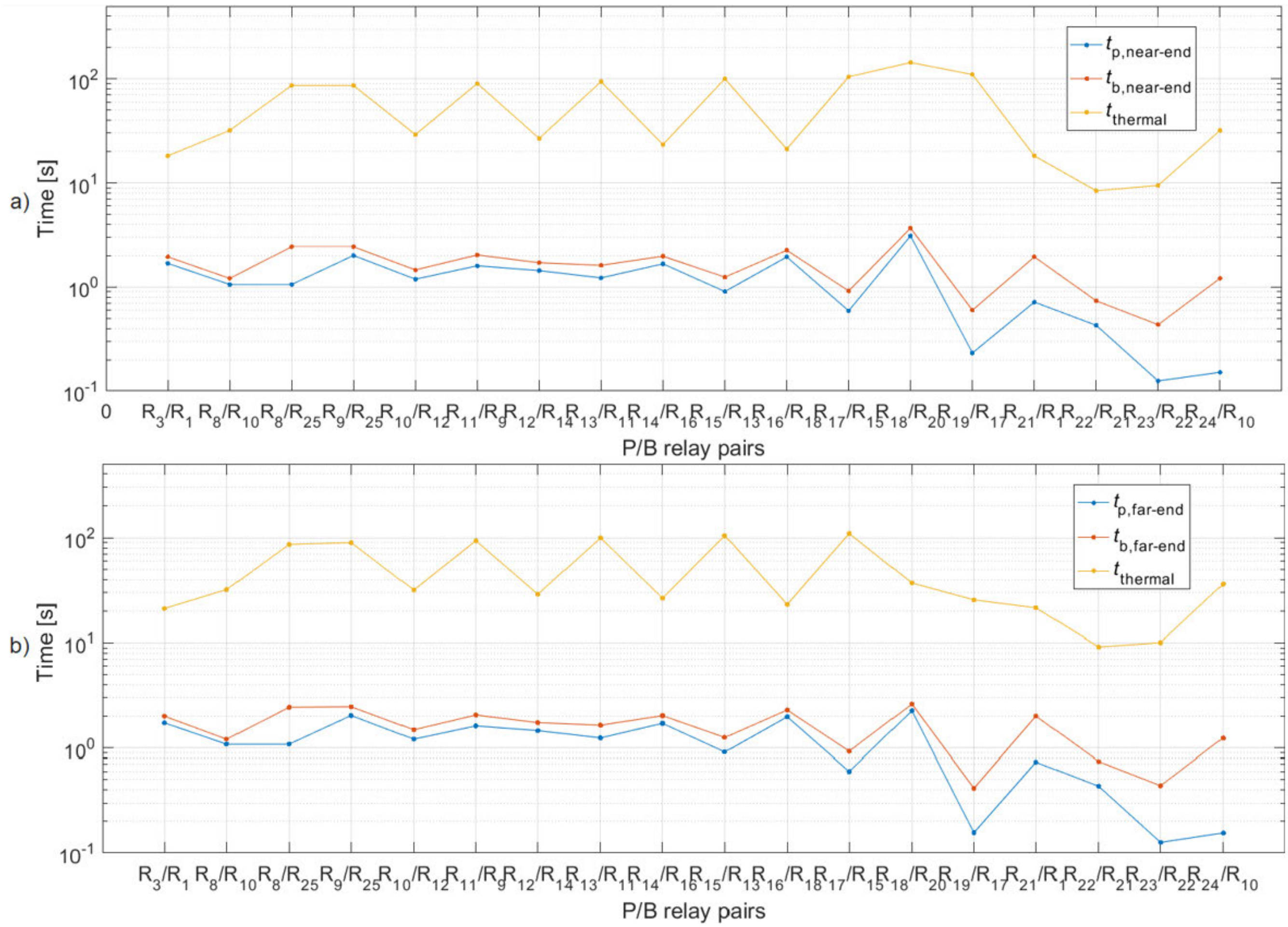

FIGURE 6. Graphs of the results presented in Table 4 for a) Near-end, and b) Far-end faults in the new configuration with line (3) disconnected.

network will also have the same settings according to the defined values in [45], obtained after the optimisation of the original looped configuration.

In Table 4, analogous to Tables 2 and 3, condensed results are shown for the case when line (3) is disconnected. They are presented for both near and far-end

TABLE 5. The summary results of the conducted analysis for the observed network with disconnected line (8).

Relay pairs P/B	Near-end fault			Far-end fault		
	$t_b - t_p \geq CTI$	t_{therm}	Δt_{therm}	$t_b - t_p \geq CTI$	t_{therm}	Δt_{therm}
R_2/R_4	0.749189 > 0.3	102,0614	101,0875	0,756648 > 0,3	105.6415	104,6576
R_3/R_1	0.313373 > 0.3	38.75387	36.52624	0.322247 > 0.3	42.45835	40.18497
R_4/R_6	0.333134 > 0.3	97.41946	96.12559	0.337702 > 0.3	102.0614	100.7498
R_5/R_3	0.312545 > 0.3	25.09425	23.14311	0.319631 > 0.3	27.87706	25.88169
R_6/R_8	0.387877 > 0.3	92.41553	90.75332	0.393823 > 0.3	97.41946	95.73177
R_7/R_5	0.263456 < 0.3	27.87706	26.20132	0.26811 < 0.3	30.21705	28.51171
R_8/R_{25}	0.786148 > 0.3	87.78746	85.36321	0.797718 > 0.3	92.41553	89.9556
R_9/R_7	0.159399 < 0.3	30.21705	28.77982	0.129014 > 0.3	30.21705	28.77982
R_9/R_{25}	1.155159 > 0.3	88.91133	86.47834	1.127222 > 0.3	89.22735	86.79191
R_{11}/R_9	0.278453 < 0.3	13.68311	12.37489	0.284126 < 0.3	15.21675	13.88188
R_{13}/R_{11}	0.255232 < 0.3	15.21675	14.16601	0.263694 < 0.3	17.99242	16.90684
R_{18}/R_{20}	0.365709 > 0.3	42.79619	40.13933	0.296053 < 0.3	20.52073	18.24243
R_{21}/R_1	1.526873 > 0.3	38.75387	36.52624	1.507975 > 0.3	38.75387	36.52624
R_{21}/R_4	0.273362 < 0.3	102.139	101.1649	0.254464 < 0.3	102.139	101.1649
R_{22}/R_{21}	0.300746 > 0.3	8.109542	7.38988	0.305148 > 0.3	8.79845	8.068255
R_{23}/R_{22}	0.302752 > 0.3	8.79845	8.373402	0.306168 > 0.3	9.363132	8.933289
R_{24}/R_7	1.289001 > 0.3	30.21705	28.77982	1.322245 > 0.3	33.89385	32.41956

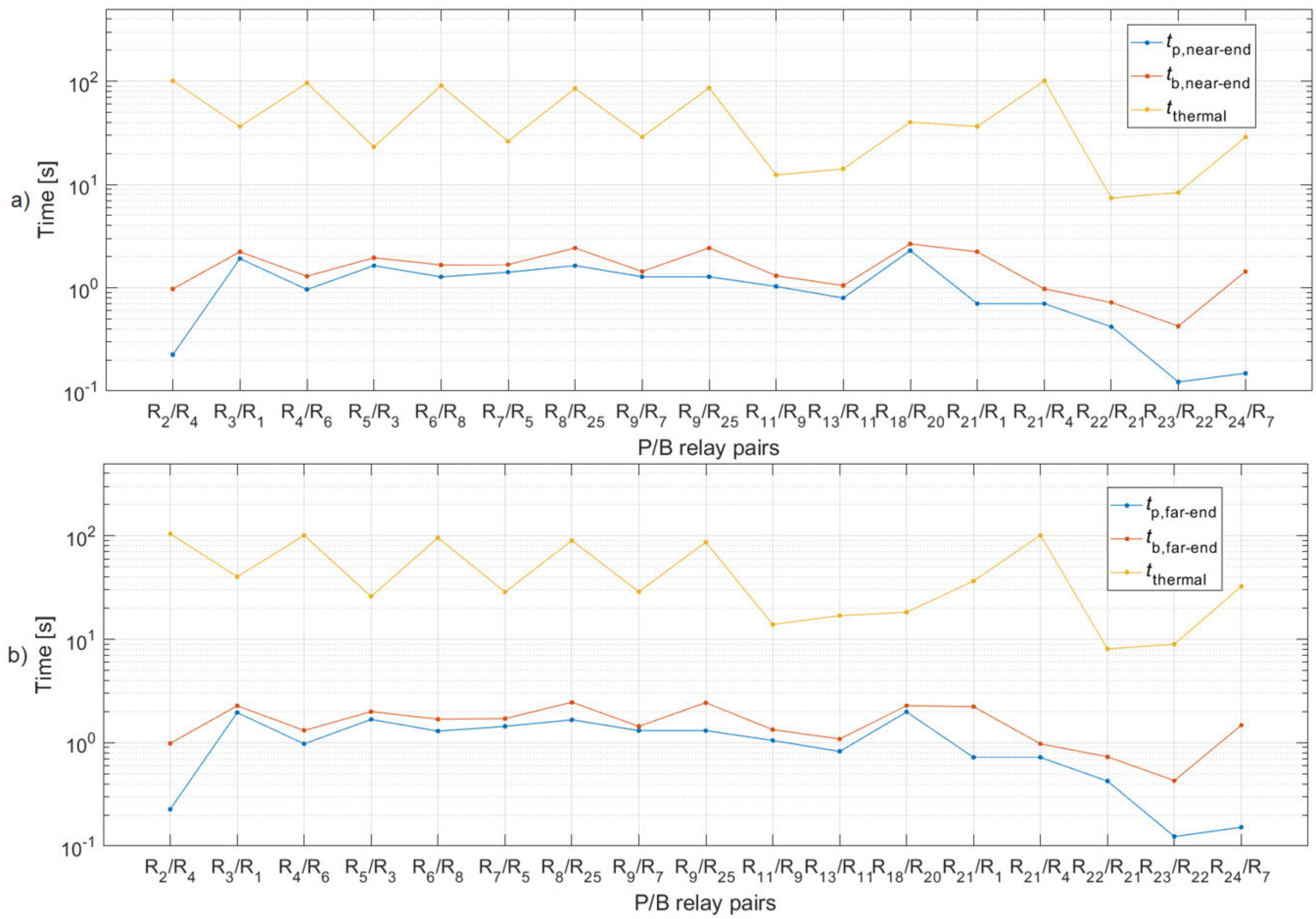

FIGURE 7. Graphs of the results presented in Table 5 for a) Near-end, and b) Far-end faults in the new configuration with line (8) disconnected.

faults of each remaining line, which, of course, must be conducted separately for this configuration. Data on the operation time of primary and backup relays are omitted for simplicity reasons, but the results of the coordination constraint check between the P/B relay pairs are shown in columns 2 and 5. The elapsed time until reaching thermal damage for each line is indicated in columns 3 and 6 for both near and far-end faults, respectively. Most importantly, the safety margin check is presented in columns 4 and 7.

Fig. 6 illustrates the operating times of primary and backup relays jointly in the case of a short circuit occurring at the beginning and at the end of each line. As before, the thermal stress curves of the protected lines in the network are also depicted, positioned well-above the operating curves of the backup relays. This only reaffirms the statement that the safety margin is satisfied in this scenario.

C. DISCONNECTED LINE (8)

For the occurrence of line (8) disconnection, relays R_{10}, R_{12}, R_{14}, R_{15}, R_{16} and R_{17} will become inactive. In Table 5, analogous to previously presented cases, condensed results are shown for the case when line (8) is disconnected. They are presented for both near and far-end faults of each remaining line, which, of course, must be conducted separately for this configuration. The coordination constraints check between P/B relay pairs are shown in columns 2 and 5. The elapsed time until reaching thermal damage for each line is indicated in columns 3 and 6 for both near and far-end faults, respectively. Finally, the safety margin check is presented in columns 4 and 7.

Fig. 7 illustrates the operating times of primary and backup relays jointly for the case of a short circuit occurring at the beginning and at the end of each line. It is noticeable that the thermal stress curves of the protected lines are clearly positioned well-above the operating curves of the backup relays. This observation serves to reaffirm again the assertion that the safety margin requirement is fulfilled effectively within this specific scenario like in the previously presented cases.

V. DISCUSSION AND CONCLUSION

This article underscores the critical importance of implementing appropriate simple and cost-effective protection strategies to enhance the resilience of observed networks amidst operational topology changes, whether anticipated or unforeseen. The authors sought to investigate the efficacy of a proposed methodology based on thermal stress curves of protected elements as an alternative to adaptive protection concepts. The aim was to demonstrate that a distribution network protection framework that remains invariant across all network configurations overcomes the challenges associated with updating a vast array of data continuously for a central adaptive protection controller. Therefore, the article conducted an analysis of OCR protection, to illustrate that the proposed methodology is not only optimal for the original network configuration, but also effective when the network undergoes configuration changes.

In a test case distribution grid, relay parameters that were optimised for the original network configuration were tested across all other potential configurations. An important distinction lies in the fact that the primary relay operating speed was critical only for the original network configuration, whereas, for other configurations, the focus shifted to monitoring potential breaches of thermal stress curves. This rationale followed a straightforward logic: while other network configurations endure for brief periods of time, relay operating time becomes less pivotal compared to ensuring the safety of equipment and network elements. Therefore, the emphasis was not solely on optimising relay settings, but also on ensuring that relays, optimised for the original configuration, neither operate excessively slowly, nor fail to act, thereby unintentionally risking thermal damage and/or destruction of the protected elements. Thus, to anticipate this problem, the optimisation was carried out in the original grid, and, besides minimising the operation time of all the primary relays, also focused on maximising the safety margin.

The simulation results indicated clearly that the risk of thermal damage or destruction to protected elements has been mitigated completely, even across varying configurations, despite certain relays not being set optimally for these configurations. This suggests that the analysis showcased the proposed methodology effectively as a highly efficient overcurrent strategy when compared with adaptive protection approaches. Furthermore, the article highlighted the proposed protection strategy as a viable and notably more cost-effective alternative to adaptive protection methods. This assertion gains particular significance considering the prevalence of a singular configuration in practical examples of distribution network operation. In essence, the article introduces a novel perspective, by emphasising the efficacy and affordability of this approach for protecting the distribution grid.

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