Trends in Power System Protection Researches: A Review of Fundamental Relays

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***Abstract*—Power system protection is one of the main element of modern energy management concept. The main task of these systems is to deactivate the faulty element or network part as soon as possible. The protection relays, called intelligent electronic devices, also have different functions than these basic functions. However, overcurrent, distance and differential protection are still used as the three basic components. In this study, current studies on these relays for coordination of the protection system have been analyzed. The research topic is limited to the main functions of the relays. Further study will examine the tasks that these relays have in providing data to the energy management system. It can also focus on the concept of wide area protection, event recording and modern communication protocols.**

***Index Terms*—power system protection, electrical safety, substation automation, fault protection, relays.**

I. Introduction

TODAY, POWER systems are very complicated structures in which production, transmission, distribution and consumption units work together at the same time. Production systems are diversified in terms of raw materials they use and conversion methods. In addition, the operations of these production centers can be government, private sector or multi-partner structures. The diversity and management of the consumption point is much more. The entire system has to be operated in conjunction with an interconnected structure. Power protection systems include the production, transmission and distribution phases of electrical energy. They are constructions aimed at using energy as safe as possible from failures or incidents that put any part of the power system in jeopardy. Making power systems 100% safe or 100% reliable is very expensive. Therefore, it is imperative to conduct risk analysis to keep the probability of failure and the possibility of being affected by failures at acceptable levels. The protection relays are the most important component of all the parameters (reliability, selectivity, speed, simplicity and economy) that are considered as the five basic features of a good protection system. The primary goal of the protection system is to deactivate the defective network element as quickly as possible. However, this is a problem that is very complex and is non-definitive for interconnected networks which are fed by multi points. Predicting all scenarios can sometimes force the protection system to work for any non-optimal case.

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If a relay is required to work for a specified condition, it must be able to adapt its settings to changing system requirements. Therefore, an improvement to be made at every stage of the protection system should include a balance between the concepts of economy-performance, reliability-security, complexity-simplicity, speed-sensitivity (selectivity) [1].

Until the end of the 19th century, in power systems mostly operated as DC, the main protection element was fusible wire fuses. In parallel with the increasing use of alternating current in these years, measurement transformers (Current Transformer (CT) and Voltage Transformer (VT)) have been developed. Thus, it is possible to detect high currents and voltages with secondary relays [2]. The concept of a protection system starting with the overcurrent, differential and directional relays from the beginning of the 1900s has expanded since 1920, including distance protection. The overcurrent inverse time relay, which was patented by C. E. L Brown in 1902, is regarded as the first AC relay [3], [4].

Nowadays, the addition of electronic and software components and the use of very different algorithms and the so-called intelligent electronic devices, relays continue to develop on the basic concepts mentioned above. Digital relays are being developed that fulfill the functions of event recording, sharing and providing statistical data, which have very important functions, especially from wide area protection and predictive maintenance aspects in energy systems. These relays are also very important in the automation of the transmission and distribution system, which is the main element of the "smart grid" concept [5], [6]. These developments make the protection systems associated with information and communication technologies (ICTs). This increases the complexity inherent in the subject [7]. The subjects for improving the coordination of the protection system in scientific research on power systems are the most studied concepts, together with stability researches.

In this study, state of art analysis was carried out on the basis of the studies made in recent years, especially over current, distance and differential protection relays. Artificial intelligence techniques, which are used to diagnose and classify failures, are also emphasized.

II. Overcurrent Relays

Over current relays (OCRs) are the most commonly used protection elements, especially in distribution systems. In radial networks fed from one side, time coordination can be achieved by using these relays alone. However, for multi-side feeds, they usually have to be used in series with a directional relay. Under these conditions, they are called as directional overcurrent relay (DOCR). Fig. 1 shows the

DOCR circuit diagram. With the use of OCRs which only operate with current information, there will be no difference between F1 and F2 faults in the system. The relays are tripped for both faults. However, the series connection of the directional relay and the OCR using current and voltage information will remain insensitive to fault F2 when the system is doing primary protection for the F1 fault. This approach provides very important advantages especially in providing relay coordination in multi-point feed grids. For primary protection, the operating time obtained from the characteristic curves of the OCR is expressed by the following equation.

$$t_{op} = \frac{\lambda \cdot TMS}{\left(I_F / PS\right)^{\eta} - 1} \tag{1}$$

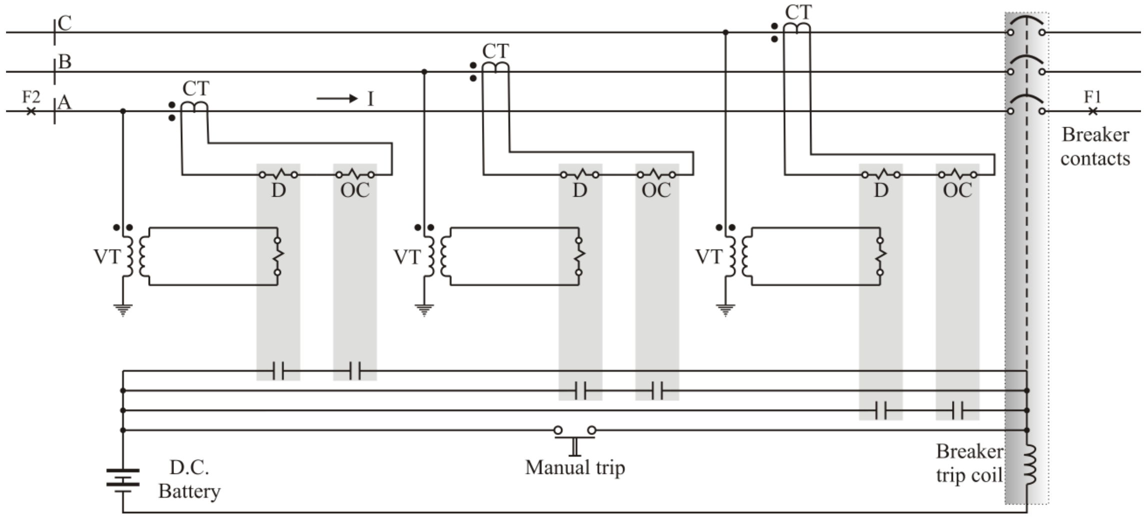

Figure 1. DOCR Circuit. OCRs use only current information. It is enough to use only CT for this. The voltage and current information must be used together to operate the directional relay. Thus, only one direction can be opened by detecting the direction of power flow.

In (1); PS and TMS represent current tap setting and time multiplier setting respectively. I_F indicates the value of the fault current flowing through the relay operating coil. λ and η are the constants which depend on the relay characteristics as shown in Table 1. Tripping time vs. current characteristics of OCRs are also given in Fig. 2.

TABLE I. CHARACTERISTIC CONSTANTS OF OCRS

Relay characteristic	λ	η
Normaly inverse	0.14	0.02
Very inverse	13.5	1.0
Extremely inverse	80	2.0

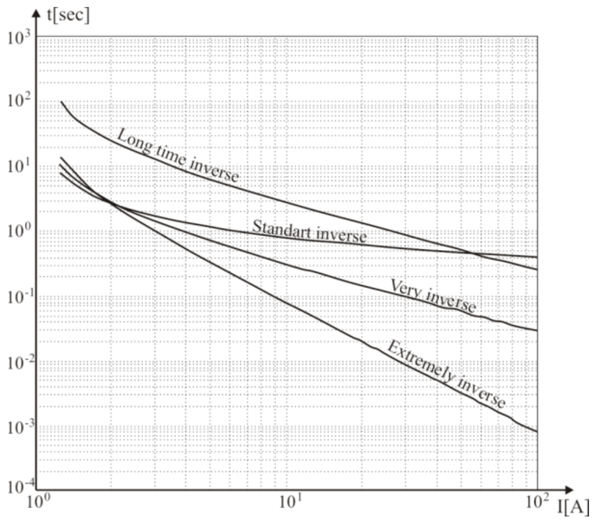

Figure 2. Tripping time vs. current characteristics of OCRs

There are various restrictions in the coordination of the relays. In a failure situation, the primary relay that should be engaged first must generally be back-up protected. This creates the necessity to define the protection coordination criterion. If a relay is defined for back-up protection $\left(R_j\right)$ of a primary relay $\left(R_i\right)$ on any k line, then the coordination constraint can be expressed in equation (2).

$$t_{ob,j} - t_{op,i} = MCT \qquad \forall k \tag{2}$$

In (2), $t_{ob,j}$, $t_{op,i}$, MCT, are the back-up relay operating time, the primary relay operating time, and the minimum time coordination range that must be left for correct operation between these relays respectively. The operation speed of the relays should be kept at an optimum value depending on the structural factors. This restriction, which determines the speed of the relay, can be expressed as;

$$t_{i,\min} \le t_{op,i} \le t_{i,\max} \tag{3}$$

Therefore, the operation time of the relay must remain between the minimum $\left(t_{i,\min}\right)$ and maximum $\left(t_{i,\max}\right)$ run times structurally. Relay coordination is also constrained by the design of the relay and the time-quadrant settings. These settings are settled gradually in discrete mode in some models. In others it can be changed linearly at certain intervals. These constraints on the relay settings are also expressed by equation (4) [8], [9].

$$TMS_{i,\min} \leq TMS_i \leq TMS_{i,\max}$$
$$PS_{i,\min} \leq PS_i \leq PS_{i,\max} \quad (4)$$

There are many parameters that affect the operating times of OCRs since they interact directly with all transient events in the transmission and distribution systems. Bougouffa and Chaghi have argued the consequences of using thyristor-controlled series capacitors used in flexible alternating current transmission systems (FACTS) with reverse-time DOCRs. The behavior of series capacitors in the event of three phase short circuit failure and the effect of operating time on DOCR were investigated using linear programming techniques with MATLAB. The results are compared to systems without capacitors [10].

In the solution of the coordination problem, tap current setting and time multiplier setting values should be calculated. The tap setting is derived from the minimum fault current and maximum load current for each relay. One of the most important steps here is the definition of constraints, especially in grids fed by multi-points. Reducing the number of constraints will also provide ease of operation. Reference [11] proposed an algorithm that first solves the optimization problem by decreasing the number of constraints. First of all, the constraints are divided into categories and the number of which cannot be considered has been analyzed and a more simple structure has been tried to be achieved. In 8-bus and 11-bus systems, a 50% to 60% reduction in the number of constraints has been achieved.

A. OCR Coordination

OCR coordination is not a scientific discipline with definite consequences. In fact, it can be described as an art with some puzzles due to its complexity and irregularity. For this reason, it is difficult to argue that it is a method that gives a definite result on a global scale. Birla et. al. have summarized the methods used in coordination of time-adjusted DOCRs in a successful review study [12]. Conventional coordination methods in large interconnected power grids can cause curve intersections and large operation times. Therefore, the use of optimization methods is generally recommended for better results [13], [14]. The following parameters are important in achieving optimal values in relay coordination;

- The optimization method used,
- Objective function,
- Type of power system (radial or interconnection),
- Nonlinear and linear relay characteristic proportional to time setting multiplier or time dial setting,
- Whether these settings are continuous or discrete mode [15].

Rahmati et al. have proposed over current protection system using local measurements without communication system. In this study, a simple solution is taken into account considering the parameters to which the Thevenin equivalent circuit of the network is connected. By using the relationship between the OCR pick-up current and the Thevenin impedance, optimization at tripping times is provided by local measurements [16].

Ezzeddine and Kaczmarek have done the optimization of the time multiplier and pick-up current parameters of the relays with known optimization techniques by taking these two parameters as independent variables. First, optimal discrete values of the pick-up current are selected. In the second phase, adequate time characteristics of the relays were selected. In the third step, the optimal discrete values of the time multiplier are found [17]. There are two general restrictions on optimal relay coordination. 1-) Physically varying run-time constraints due to relay characteristics. 2-) Coordination constraint in determining the time interval between primary and backup relays. In literature, the effects of these restrictions are taken into account by various methods (barrier, punishment, etc.). So and Li have developed a model based on evolutionary programming for OCR coordination in ring distribution systems. The conventional optimization techniques fail because the coordination problem involves optimal points at every local point. The proposed model is much more successful than the classical mathematical optimization techniques.

This algorithm can be used in all overcurrent adjustments and provides the ability to control the correct coordination in all system constraints. Relay operations resulting from changes in the fault current distribution due to circuit breaker operation while the fault continues are also analyzed [18]. Papaspiliotopoulos and his et al. have recently addressed the coordination problem with a new approach using the equivalent quadratically constrained quadratic programming (EQCQP) model. The proposed method has greatly increased the efficiency of the optimization software in particular [19].

Linear programming (LP) and evolution algorithms (EA) are also used to solve the DOCR coordination problem [20], [21], [22], [23]. Pick-up current and trip time optimization studies using Mixed Integer Linear Programming (MILP) are also included in the literature [24]. Shih et al. compared different versions of differential evolution (DE) algorithms in the coordination of DOCRs used in large interconnected grids. Analysis criteria are1-) in addition to maintaining selectivity, the value of suitability for minimizing the working time of primer and back-up relays, 2-) the number of violations of coordination constraints and 3-) the standard deviation of the process time. Developed DE gives the best results in terms of execution time, result quality, robustness and convergence ability compared to others analyzed in this study [13]. The DE algorithm was previously compared with the application results of the teaching learning-based optimization (TLBO) algorithm to provide optimal coordination of DOCR [25].

Reference [26] compared the performance of solving the coordination problem of DOCRs of five different metaheuristic algorithms. Time coordination values of DOCRs were analyzed by running Genetic Algorithm (GA), Particle Swarm Optimization (PSO), DE, harmony search algorithm (HS) and seeker optimization algorithm (SOA) 100 times under the same initial conditions. It has been determined that the DE algorithm always provides the lowest value by using the minimum opening time and coordination time interval, and also gives the best values when the relay characteristic curves are different. It is also determined that the values obtained by the DE are more predictable because of the low standard deviation.

Bedekar and Bhide used a continuous genetic algorithm (CGA) technique for optimal DOCR coordination in a ring feed distribution system. Constraints have been incorporated into the fitness function using the penalty method. The results has shown that the proposed model faster and requires less storage space than GA based on the classical binary number system because it eliminates the decoding process of chromosome codes [27]. A recent study on the use of GA in relay coordination was also carried out by Bottura et al. Here, however, the best time-quadrant value is obtained using a LP model. The value of the pick-up current is defined by GA. In the model called hybrid genetic algorithm (HGA), the short circuit current direction is considered. The obtained results are compared with known mathematical programs such as AlphaECP, BARON, BONMIN, DICOPT, KNITRO and SBB. In order to demonstrate the validity of the results, a real network system is considered. It has been shown that the proposed model shows 12-27% more optimal values than the conventional methods in determination of tripping time and pick-up current values, and the relay coordination is improved by these reductions [28]. Tahkur and Kumar have presented an optimization solution consisting of a bounded exponential transition and power mutation (BEX-PM) and a real-coded GA(RCGA) for the purpose of detecting optimal relay settings and at the same time minimizing the difference between backup and primer protection relays [29]. Protection optimization based on GA for a 7-ring ring system including transformer protection was performed by Chen et al. [30]. References [15] and [31] are also examples of GA-based selectivity studies.

In recent years, chaotic firefly algorithm (CFA) has also been the subject of studies on optimal relay coordination in the literature. In [32], MATLAB based CFA is presented for optimal time coordination of OCRs and the results are compared with classical firefly algorithm (FA). Meskin et.al. have focused on the identification of coordination starting points in OCR coordination in the case of multi-sided faults. In single-sided grids, the coordination is naturally started from the farthest relay to the source. However, the choice of coordination starting points is an important challenge for interconnection systems. The authors attempted to establish relay coordination by developing a procedure for finding breakpoints in these network. The proposed model especially contributes to the reduction of processor time in systems with many relays [33].

In order to solve the optimal coordination problem of DOCR, Mancer and colleagues have developed a PSO-time varying acceleration coefficient algorithm that takes the optimum pickup current as a discrete parameter and the TMS as a continuous parameter. The computation results with the proposed method are compared with the calculations made with MATLAB-GA, classical PSO and other techniques, and the algorithm has been shown to improve the solution of the problem [34]. Modified PSO algorithm is also presented to eliminate problems such as determining the starting point of the relay coordination, re-scanning the entire system in each iteration and based on the possibility of changing particle positions in each update in the classical PSO algorithm [35].

Bouchekarave et.al. used the modified electromagnetic field optimization (MEFO) method for shortening the operation time of DOCRs and for optimal coordination. The EFO approach is based on the behavior of electromagnet particles in different polarities. In EFO, each electromagnetic particle force is generated using a random number distributed uniformly between 0 and 1. By producing a new electromagnet using three parameters obtained by multiplying by a factor depending on the magnitude of the force, a more balanced output is obtained in the production strategy. This study also deals with Constraints by means of a penalty method. The results show that the proposed system works efficiently in shortening the relay operation time for optimal coordination of DOCRs [36].

B. OCR Modifications

Enriquez and Martinez has developed an adaptive function to increase the sensitivity determination of pick-up current of time delaying OCR. Reduction in load and increment in rated current causes that to observe as a fault current in some situations. This can cause mal operation of relay. In the proposed model, modification of the pickup current is made to be dynamic so as to respond to the operating conditions of the grid [37]. Directional relays have been used in protection of multi-point fed power systems since the 1950s. It is known that the conventional direction relays operate with voltage and current information and are used in different connection modes in determining the fault location. Directional capability is especially important in overcurrent and distance protection.

The conventional DOCRs use the reference voltage as the amount of polarity to estimate the direction of the fault. In the case of close disturbances, this traditional method can lead to false openings. Nojavan et.al. tested OCRs by providing a directional relay algorithm that uses only current signals for fault diagnosis. Because it does not require a phasor estimation, it offers a faster and simpler solution than traditional methods [38]. It has also been studied in the literature that digital signal processing based algorithms using fuzzy logic controller (FLC) can improve the operation time and accuracy performance of overcurrent relays [39], [40], [41], [42]. Hybrid use of FLC and artificial neural network (ANN) algorithms can improve DOCR's time quadrant and operation time values. The current multiplier and operation time curve values are transferred to a graphical axis plotted with the fuzzy approximation and given as the input to an ANN trained with data obtained for any trip time. Thus, the non-linear operation time and the time-quadrature relation are analyzed by ANN and the tripping time is determined [43], [44].

III. Distance Protection

In high voltage (HV) and ultra-high voltage (UHV) power systems, 85% of failures occur in transmission lines. Incorrect opening or undoing may cause unacceptable results in these systems [45]. Distance relays (DRs) offer optimal solutions for line protection, especially in grid systems. The distance protection is generally designed according to three zone protection principle and uses line impedance information. The first zone is the primary protection zone, covering 80% of the first line observed by the relay. For the second zone, backup protection is done by setting the impedance of the primary line to 1.2 times. Remote backup protection (zone 3 protection) is quite challenging in terms of coordination. Practically, the impedance value is taken as the sum of 100% of the first line and 120% of the second line. In some cases it may become impossible to coordinate the third zone protection [46]. Figure 3 shows the general structure of the distance relay connection circuit.

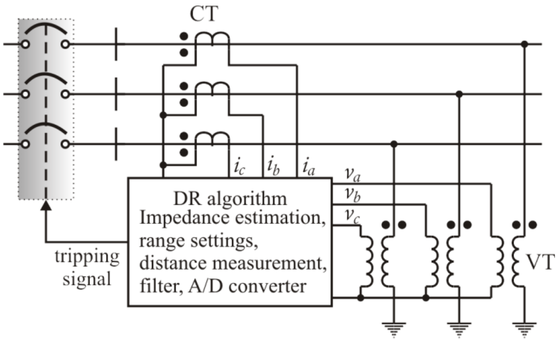

Figure 3. Distance relay circuit. VTs, CTs, impedance measurement system and directional sensitivity are standard. Various DR algorithms are used for distance determination, fault detection and classification. Filters reduce EMC effects on current and voltage signals. Analogue / digital converter systems have become the standard for digital relays in particular.

There are also some applications in the literature that aim to avoid mal operations with some modifications by way of the above conventional logic for remote backup protection [47]. Third zone settings in DRs apply as a firewall against the possibility of failure of the primer protection in remote substations [48]. However, mal operations in Zone 3 are among the most important causes of major energy interruptions in various countries. This inconsistency is caused by the overloads in zone 3 distorting the settings. It is difficult to draw the boundaries of the overload concept or to determine the overload only from the instantaneous current values. For this reason, Zone 3 protection can be replaced by computerized solutions based on pilot relays or artificial intelligence algorithms used today [49]. In the third zone coordination of DRs, various systems are designed to adaptively adjust the settings of relay by communicating with neighboring distribution stations [50]. DRs are called impedance relay or modified relay (mho relay) according to the range finding functions that make up the trip region (Fig. 4).

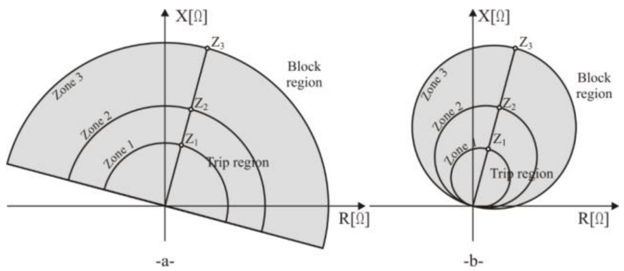

Figure 4. Zone protection with distance relay a-) Directional Impedance Relay, b-) Admittance (Mho) Relay.

The presence of FACTS controllers also causes mal operation of the DRs. Serial-parallel FACTS devices have greater impact on relay performance than other FACTS devices. Furthermore, due to the high resistance values of these devices, the relay cannot reach this impedance value and cannot detect the fault correctly. In a recent study, a structure was presented to detect the imbalance by calculating the active power from voltage and current values of buses. In addition, a technique for the calculation of unified power flow controller (UPFC) data has also been proposed in this study. The resistance that occurs at the UPFC and the fault point increases the impedance measured by the DR. In this case, the relay does not switch on. In the proposed method, first, the fault point resistance is detected by calculating the active powers at both ends of the transmission line. In the second step, using the transmitted data, the voltage and current values given by the UPFC to the system are calculated. This value is subtracted from the impedance measured by the relay. The method is based on active power calculation. For this reason, the capacity and inductance values of the transmission line have no effect on the result [51]. References [52], has also taken into account that the presence of FACTS and static VAR compensators (SVCs) makes fault detection difficult in terms of DRs. It is based on the identification of the impedance measured at the operating point of the relay and the characteristic impedance of the relay for phase-ground and phase-phase faults in the case of SVC in a transmission line. Thus, it has been tried to make a stable distance protection at different compensation levels with SVC. Reference [53] proposed a transmission line protection model with pilot protection approach in which DOCR and DRs are combined. The OCR performs the back-up protection function for phase-ground failure. The DR carries out the protection of faults phase to phase. In order to determine the set values of the relays, a model using GA is presented considering the characteristics of maximum load, current and minimum fault current of the line.

Zubic et al. presented a new DR algorithm based on Maximum Overlap Discrete Wavelet Transform (MODWT). In this study, orthogonal filters based on the Fourier and Hilbert transform approach are used, especially for phasor estimation. As an alternative to traditional Wavelet Transform (WT) based phasor identification solutions, the proposed model was tested to verify the protection speed and reliability. It has been determined that it accelerates the operation time by around 10ms according to the conventional methods [54]. An adaptive transmission line protection system design based on synchronous phasor measurement units is also presented in reference [55]. Positive component voltage and current vectors at both ends are used to determine the line parameters and the fault point on the line. The proposed model has been demonstrated to be used in single-double circuit lines and to work steadily against power oscillations. A model reference [56] is also presented for testing the security and reliability of DRs.

For these calculations, it is necessary to statistically regulate the event records of the line that the relay is connected to. This demonstrates that the next generation distance protection systems must also include event recording functionality. Reference [57] also compares the classical harmonic filters (Cosine or Fourier) that filter the fault components embedded in the fundamental component of current in the DRs and Prony filter. Campos et.al. also compared the time response and frequency response for four classical phasor estimation methods by improving the filtering of undesired frequency components of the signals. The performance of the proposed model was tested by digital DR application [58]. Signal distortions caused by the saturation effect of the measuring transformer, which provides the current information of the DRs, can be caused by incorrect operation. The Elman Recurrent Network (ERN) model in reference [59] is presented to remove the disturbing effects from the current signal and to reduce the deviation from the correct opening point. In case of earth faults caused by high impedance, values close to or above the impedance value set by the relay can occur. This may cause the DR not to trip. The drawbacks of operating with only impedance value in this type of malfunction are also subject to literature studies. Li and Lai have tried to define the ideal operating region for DRs by examining how active and reactive power flows in the line change in the event of such a fault [60]. The primary task of DRs is to protect transmission lines. However, harmonics in voltage and current signals and exponentially decaying DC components negatively affect relay performance. A method is proposed in reference [61] that focuses on estimating DR impedance by reducing the degree of disruptive effects described above with phasor estimation using ANN. This method continues to calculate the apparent impedance during the training of the ANN, given in the system online, using a multi-layer sensing architecture to estimate current and voltage signals. ANN is also subject to different studies aimed at reducing range errors in distance protection [62]. A model based on ANN training for identifying admittance relays' trip and block regions for first zone protection is presented in[63]. Load curtains or overload elements are used to prevent DRs from mal operations under heavy load conditions. These components try to keep relays in a block state when there is an overload in the system. ANN is used to distinguish overload conditions from fault conditions, especially those with low power factor overloads or small fault resistance [64].

When DRs are used on very long transmission lines, due to their high capacity values, measurement accuracy and measurement stability through complex and considerable harmonic components are adversely affected in conventional systems. As a result, the tripping speed may be somewhat reduced. To solve this problem, Wen et al. proposed a new DR algorithm for long transmission lines based on the differential equation algorithm using the pi-equivalent circuit of the transmission line. Current at the relay point and voltage at the fault point (high-frequency signals filtered with low-pass filter) still apply in systems with original distributed parameters. For this reason, the differential equation algorithm can be applied to transmission lines using pi-equivalent circuit [65].

In very long transmission lines, only one zone distance protection can be applied. Araujoa and Pereira have developed a non-iterative first-zone DR for detecting a phase-to-ground fault in long parallel transmission lines. It has been taken into account that neglecting the propagation effects of shunt capacitance by processing the line solely in terms of serial impedance may cause a significant fault in impedance estimation at long distance lines. In the proposed algorithm, the shunt capacity is produced from a distributed parameter which is fully taken into account for the mutual impedance and admittance values and is applicable to long parallel lines. The proposed model identified the fault location with an error of less than 1.8% for 85% of the total line length of 800 km [66].

Proper coordination between DRs and DOCRs in interconnected systems is important for system security. Reference [67] has addressed this problem and developed a problem formulation for the optimal coordination of DRs in the system where DOCRs are included as backup relays. Later, to overcome this complex problem, multiple embedded crossed PSO has been proposed. A successful study to determine the delay time of DRs in remote backup protection (zone 3 protection) was presented by Lukowicz et al. In the application based on the event tree risk analysis technique, a time dependent fault tree is created and the delay adjustment of DRs is selected for remote backup protection. By taking into account the natural delays of the relays and interrupts in the chain system, the events requiring the remote backup protection are logically connected to each other with time-dependent failures [68]. In systems where differential relays and pilot protection do primary protection, DOCRs serve as back-up protection. In this case, the behavior of DOCRs in large networks included distance relays also becomes important. Reference [69] provides a solution for ensuring coordination between the distance protection and DOCRS under these conditions. In another similar study, Marcolino et al. tried to provide optimal coordination using GA in a system where distance relay for phase-to-phase and DOCR for phase-to-ground failures [70].

IV. Differential Protection

Differential relays (DFRs) are used for rapid cleaning of internal faults in generators and transformers. Therefore, additional algorithms such as coordination and backup protection are not required. However, it is possible that these relays, especially due to the saturation effects of the CTs, can be tripped in the external faults or in the case of start-up process of transformers. Fig. 5 shows the general block diagram of the DFR and the internal and external fault opening zones.

Reference [71] used Fast Fourier Transform (FFT) to generate a constraint signal to prevent the relay from operating in the event of an external failure. A scheme for enhancing the safety of differential numerical relaying with second order harmonic generation is presented. Tripping signal of the differential relay is produced by comparing the vectors added to the secondary currents of the current transformers with the previously set value. The constraint signal is produced by comparing the second harmonic of the differential current with the algebraic sum of the second harmonics of the individual secondary flows.

An innovative scheme was developed in reference [72] that can observe and distinguish the behavior of power transformers under different operating conditions (such as rated load, inrush magnetizing current, over-excitation of the core, CT saturation due to internal and external failure). The PSO approach is used to train dual-layer feed-forward neural networks and to distinguish different operating conditions. Two different ANN schemes were used as hybrids. The first one is the internal fault detector. The other is used to identify and define different operating conditions such as normal, inrush current, over excitation, and CT saturation due to external malfunctions.

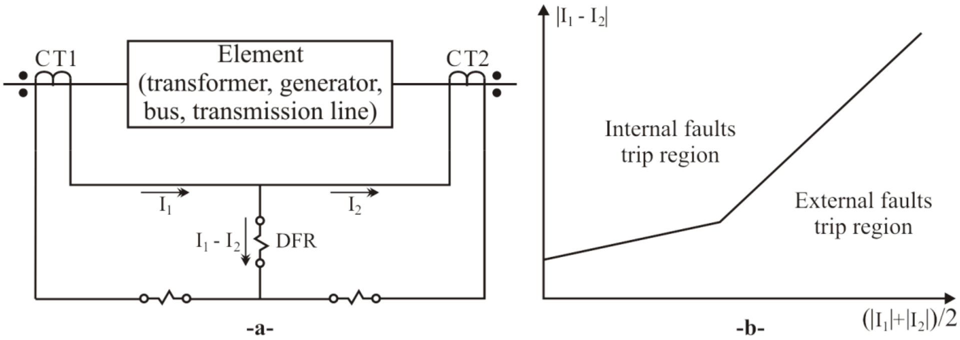

Figure 5 Traditional differential protection a-) circuit diagram (can be applied to transformers, generator, buses or transmission lines) b-) trip region characteristic.

Inrush magnetizing currents (startup currents) in transformers are an important influence that increases the risk of incorrect operation of DFRs. The distinction of these currents from actual fault currents can be achieved by comparing the two current behaviors in terms of phase angles [73], [74]. In addition, analysis of the primary and secondary currents, the transformer end voltage and the voltage values at the load ends is also necessary to make the distinction between internal and external faults more accurate. These comparisons can be achieved by the differential stability of the differential relay, its safe operation, the increased immunity to sudden magnetizing currents, and the more stable operation in external faults that contribute to saturation effects in current transformers [75]. Differential protection has also been used in power transmission lines in recent years. The [76] introduces a DFR method for transmission lines that is used spectral energy information provided by Fast Discrete S Transform (FDST). Unlike the classical S-Transform technique, frequency scaling, bandpass filtering and interpolation techniques have been used in different types to reduce the computational burden and eliminate redundant backup information. Due to the low computational complexity, the proposed algorithm is also suitable for real-time applications.

Reference [77] presented a model based on the energy conservation law for the differential protection of transmission lines. The active power values at both ends of the line (supply and load) are compared with a specific value previously determined. If the result is greater than this value, the result is an internal fault on the line. Power signals are used as input. A new limit has been set depending on the loss of the maximum power drawn from the transmission line. The proposed method is also suitable for long lines and underground cables. A similar differential protection algorithm using energy information is presented in a more recent study. Reactive currents due to increased capacity effect on long transmission lines prolong the operation period of DFRs. In order to overcome this drawback, the approach of measuring the momentary energy flows at both ends and comparing the energy consumptions of the line elements has been adopted. Since the line elements are fixed, it is necessary to have an energy balance at the input and output ends under normal conditions. When this equilibrium is broken, it is decided that there is an internal fault on the line [78]. In wide area protection concept, differential protection of transmission lines is an important element. Differential approach with pilot protection logic at both ends of the transmission lines increases the reliability of the protection system [79], [80].

V. REAL-TIME FAULT DETECTION WITH ARTIFICIAL INTELLIGENCE TECHNIQUES

Artificial intelligence algorithms such as FLC, ANN, adaptive neuro-fuzzy inference systems (ANFIS) and wavelet transform (WT) can be used as stand-alone or hybrid especially for failure classification. The most important reasons of this are the development of high-speed communication technologies, and the elimination of the time gap between long distances with the global positioning system (GPS).

In WT analysis, the current and voltage signals are separated and compared to the components during the process of tripping of the breaker, which is formed by failure, fault process and start of fault. It is intended to identify extreme and abnormal changes by removing the electromagnetic noises from signals [81]. It is possible to analyze the current signals taken from both ends of long transmission lines with the same time and analyze it with WT technique. Thus, a differential protection operated with the pilot relay logic in which the fault conditions occur can be provided [82], [83].

ANN has been a subject for many years for fault detection and classification studies to assist the protection relays. Generally, training of the ANN with the values of the steady-state normal operation data and the values of the defective state behaviors can be regarded as the first stage [84]. The voltage and current in case of failure can be determined more quickly by taking the normalized peak values of the fundamental wave forms input data to the network [85]. Sidhu et al. presented a method of fault detection based on analyzing the radiation generated from arcing faults. In the proposed model, acoustic, infrared and radio waves are recorded with appropriate sensors via digital signal processor (DSP) based data acquisition (DAQ) system and classified by ANN [86]. WT and linear discriminant analysis (LDA) based fault detection and classification methods for symmetric and asymmetric faults in dual circuit transmission lines are proposed in Reference [87]. The method was tested several operating conditions such as CT saturation, power flow changes, different failure types, fault impedances and fault startup angles. It has been determined that the proposed method can perform fault classification at 99% accuracy.

It is difficult to distinguish faults from normal switching operations when detecting faults over high impedance. This problem is the subject of study in the literature. Baquiet et.al. used a hybrid WT-ANN approach in classifying high impedance faults. The current waveforms generated under different transient conditions are processed by WT in the time and frequency domain and sent as input to the pre-trained ANN [88]. Travelling wave protection is used as a fault clearing method especially in very fast transient regimes. It is based on the determination of the time difference between the incident wave and the wave at the fault point [89].

A hybrid system reference [90] has been developed that uses data obtained from voltage and/or current signals separated to the components with the WT during faults. The fault point is determined by an algorithm that combines the travelling wave theory and impedance calculation on this data.

Abu-Elanien et.al. successfully detected internal failure on the HVDC line, which was fed from multiple sides by means of a two-ends travelling wave theory. For the synchronization of the relays at the two ends of the long transmission line, the GPS time data is used. The detection of the fault was made by DWT with high frequency transient regimes [91]. It is possible to eliminate the need for communication between ends in HVDC lines. For this, the algorithm based on the analysis of the high and low frequency components of the current at only one end with WT is presented in Reference [92]. In this case, the internal and external fault discrimination is provided by the shunt capacitors which are added to the system and filter the high frequency transient regime waves that occur in the external fault.

VI. CONCLUSION

In this study, a study covering recent developments in overcurrent, distance and differential protection, considered as the most basic relays for the protection of power systems, has been presented. In power systems it is essential that a good protection system is operated at the highest standards, especially in terms of selectivity, speed, reliability and safety. However, the complexity of the systems and the necessity of working together on a large number of relays makes the exact solution impossible for these concepts. For this reason, researchers try to improve the parameters above mentioned by using artificial intelligence techniques to optimize certain parameters or to help relays by focusing on various points.

The main problem with OCRs is the shortening of the tripping time and the improvement of the selectivity. Researches are mostly focused on detecting the malfunction and improving the cleaning time. In addition, the optimization of the coordination time between primer and back up protection is discussed in detail.

Incorrect operation of remote backup protection in distance relays poses significant problems. Remote backup protection becomes more difficult as the line length increases and the effect of elements such as SVC and FACTS on the line. For this reason, distance relays, especially zone 3 protection, can make unnecessary trips in overload situations. In addition, there are problems such as not being able to detect high impedance faults. This situation can cause very important energy interruptions. For this reason, the studies focus especially on the coordination of zone 3 protection and fault identification processes.

Differential protection is an effective method of internal fault detection applied mostly to transformers and generators. However, recent studies have focused on the use of differential protection in transmission lines, especially with the reliability and speed of communication and pilot protection between distribution centers. Optimization studies are also carried out to ensure that DFRs are insensitive to start up currents of generators or transformers, CT saturation, and sudden magnetizing currents. These investigations include the identification of internal faults in transmission lines by the differential protection approach.

In recent years, the use of artificial intelligence techniques has become widespread, especially in real-time troubleshooting. The failure models are presented with the models of current, voltage, power factor, symmetrical components, and analysis of the parameters using artificial intelligence techniques. Even in the future, the protection of the power system will be the main element of the smart grid concept. It is envisaged that efforts to improve the performance of the protection relays will be expected to increase in order to reduce the detrimental effects of factors such as varying producer/consumer structures, hypersensitivity to energy interruption. In future studies, it is aimed to refer to the functions of protection in modern energy management systems, communication technologies and failure (event) recording processes.

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BIOGRAPHIES

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