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DESIGN OF A FUZZY DISTANCE RELAY TAKING INTO CONSIDERATION THE IMPACT OF USING A UNIFIED POWER FLOW CONTROLLER

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The compact design of a fuzzy distance relay, which includes its impact on using a unified power flow controller in a power system, has been adopted as the object of the study. Traditional power system grids have increasingly widely used flexible alternating current transmission system devices in recent years to increase power system stability when faults, unbalance, and sudden changes in load occur. This plays a role in improving power quality, power factor corrections, and power flow control. A unified power flow controller is one of these devices that is most used, popular and meets these benefits, but it simultaneously gives a different change in the apparent impedance of the protection system due to its design. To overcome these issues, the proposed novel design of a fuzzy distance relay is made with the assistance of MATLAB® Simulink and Neuro-Fuzzy Designer. The proposed design work was divided into three parts, the first without fault and the second one including four scenarios without using and using a unified power flow controller in different transmission line locations. The design was carried out in the third part after collecting all input-output data sets. This paper offers an efficient design method, which depends on the input value of the observed apparent impedance, also known as resistance (R), and reactance (X). The output is a trip signal to the circuit breaker when a fault occurs. The advantages of the proposed design are a fast-clearing time of 1.42 ms, and working when utilizing a unified power flow controller in different locations; the results show a fast clearing although the long impedance trajectory for some cases. The fast fault clearing will make the system more stable and overcome the maloperation of the distance relay

Keywords: Flexible Alternating Current Transmission System, Unified Power Flow Controller, Neuro-Fuzzy Designer, Protection Systems

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1. Introduction

As a direct consequence eht fo increased demand for electricity, the structure of electrical power systems has become noticeably more sophisticated. To protect such a system, many protection devices are used. The distance relay was utilized primarily for transmission line protection of the power system because it provides fault clearance and system coordination. Distance protection may suffer from maloperation due to added new devices or modifications that change the power swing [1, 2].

To optimally solve the stability issue for the power system, one solution could be a Flexible AC Transmission System (FACTS), which improves voltage stability and increases power transmission capacity. Nevertheless, FACTS devices dynamically change power systems as they strongly affect the settings of the existing transmission line protection scheme. Fig. 1 [3] displays a group of FACTS controllers based on voltage-sourced converters (VSCs). However, when the FACTS device is a part of the fault circuit, it affects the measured impedance of the distance relay. Although this is largely true in most systems, its intensity depends on the device type, network connectivity, and operational information characteristics. A complete protection study should be conducted prior to installing a new FACTS device on an existing transmission system configuration to assess the present protection settings [4–6].

A unified power flow controller (UPFC) is one of most FACTS devices that affect the transmission line impedance between two connection buses because it comprises two connection circuits, series and parallel. Therefore, this modification (adding UPFC) must be included in the design of the distance relay to ensure working with varying fault impedance trajectories.

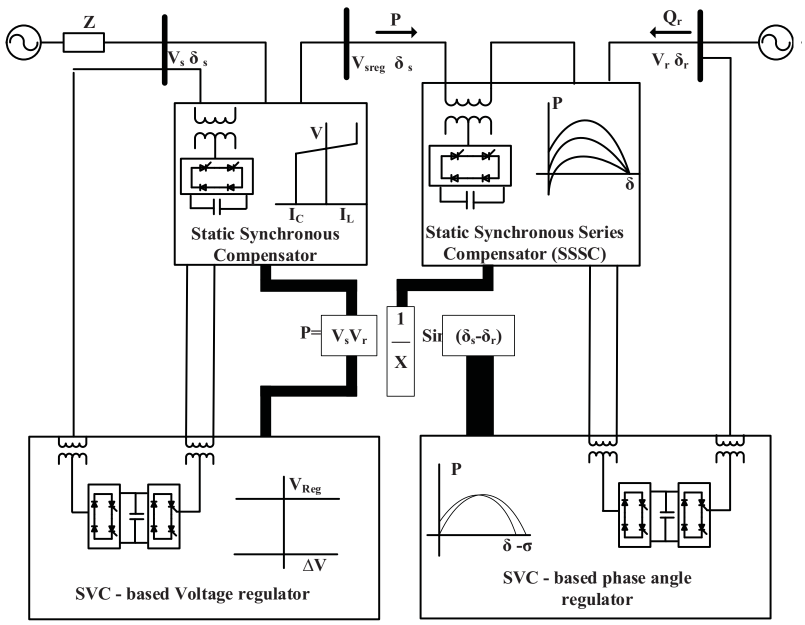


Fig. 1. A group of flexible alternating current transmission system controllers based on voltage-sourced converters

2. Literature review and problem statement

FACTS devices change the distance relay's perceived impedance, and UPFC is one of the most effective. Gyugyi was the first to propose the notion in 1991. As it provided the multipurpose flexibility required to address various challenges in the power supply industry, it was developed to deliver real-time control and dynamic compensation in transmission lines. A UPFC consists of a series and a shunt converter that provide active and reactive control of the power flow in a transmission line as well as active control of bus voltage. Moreover, UPFC works as a static synchronous compensator (STATCOM), a static synchronous series compensator (SSSC), and a combination of them [7].

As the use of FACTS devices has increased, so too has the number of studies on conventional distance relays and methods of protecting multi-terminal lines that can be equipped with FACTS devices. Previous FACTS research only evaluated traditional distance relays. The scientific work [8] presents the results of a thorough model of a transmission system using UPFC, showing the distance relay's effect when UPFC is operated as STATCOM only and as UPFC (STATCOM + SSSC). However, there were unsolved concerns related to different faults and UPFC placements, possibly due to model complexity. More research can help solve these issues and change the relay-tripping boundaries approach. This approach was used in [9]; however, the presence of SVC influences the trip boundaries of the relay's phase-to-ground fault measuring units. Consequently, it is beneficial to investigate the boundary that must be adapted and managed with the zero-sequence current in the SVC's coupling transformer's primary connection. The results from [10] show the adaptive distance protection scheme in the presence of SVC. It is shown that the recommended configuration adaptively increases relay zone-1 distance and appropriately decides the relay trip. However, SVC's objective impossibility remained unsolved. Knowing the SVC transmission system and operation modes might help solve these issues. The study [11] describes the research findings on a fuzzy-logic-based method for addressing the influence of a STATCOM device put within the relay reach of the phase 21 protection relay. While the existence of STATCOM could cause the traditional mho relay to operate incorrectly in the case of each phase fault on the line selected within the relay's reach, the suggested adaptive fuzzy relay could issue the right trip signals for the same fault conditions. Still, there were unresolved issues related to maloperation. A way to overcome these difficulties is by making studies under miscellaneous conditions like CT saturation. A similar approach was used in [12]; however, disregarding the line's shunt capacitance will also cause the distance relay to overrun with a smaller probability than underreach. Due to the significant possibility of underreach, conventional tripping characteristics like the quadrilateral cannot fulfill SSSC compensated transmission line protection criteria. All of this indicates SSSC configuration investigation. The researchers in [13] present distance relay characteristics with SC for line-ground, line-line, and other faults. The accuracy and dependability of modified distance relay compared to the normal relay design are shown. Maloperation difficulties remained. Studying the relay algorithm may help. The paper [14] presents the research results on designing and implementing a Grey Wolf Optimizer (GWO) Fuzzy PID controller for the governor of the generator unit. The system's dynamic performance is improved largely with the proposed controller compared to TLBO-optimized output feedback SMC. But there were unresolved issues related to GWO optimized Fuzzy PID controller. A way to overcome these difficulties can be to compare different FACTS controllers for AGC with the proposed controller. This approach was used in [15]; however, the deployment of the novel PD-Fuzzy-PID cascaded controller in the conventional multisource system was constrained by analysis. All of this indicates that it would be prudent to conduct research on renewable source systems and microgrids for automatic generation control. The results from [16] show a new method for calculating apparent impedance seen by the distance relay location. At the same time, a short-circuit fault occurs in a transmission line connecting the SVC to the midpoint of the line. This method provides fast calculation and robustness for identifying different fault types in power systems. A way to overcome these difficulties can be by making more studies about a phasor measurement unit (PMU). Assessing how the effectiveness of transmission line distance protection is affected by intermediate sources is explained in [17]. The work [18] examined the efficacy of conventional distance protection for TLs with infeed in the presence of SVC when faults occurred in two zones. The study [19] describes state-of-the-art models and methods for analyzing and regulating UPFCs in smart power systems, analyzing and classifying present and future research trends. Intelligent control schemes and sophisticated control methods are the most common UPFC control approaches. Various realistic heuristic approaches are utilized to solve the UPFC allocation problem. UPFC control algorithms with reconfigurable architecture, wide area coordinated control algorithms, new models, methods, and simulation tools for integrating UPFCs into smart power system operations and planning can all help to overcome these challenges. The paper [20] examined using an mho-type distance relay with three zones for a variety of faults in different places and highlighted the potential benefits. A novel method for solving the problem of high-resistance faults for the current traditional distance relays of parallel transmission lines was proposed in [21]. The study [22] used a wavelet-alienation-neural (WAN) method to analyze faults in UPFC-compensated transmission networks. Wavelet-estimated coefficients were calculated from current signals to detect and classify distinct outages. Furthermore, an artificial neural network that was fed approximation coefficients that had been estimated from the voltage and current data of the same quarter cycle was able to execute precise fault localization. The work [23] proposed the eigensystem realization (ER)-based identification technique and Z-domain method (ZDM) to enhance transmission line impedance estimation under fault situations by eliminating the exponential decaying DC offset from distance relay current data. The paper [24] introduced an innovative experimental approach to get the offset mho characteristic of memory-polarized and cross-polarized distance functions of protective relays. Because the offset impedance is dependent on power system conditions, a suitable testing procedure for these parameters is not readily apparent. Since the suggested approach is directly targeted on the relay, it is independent of any power system model.

All previous literature results discussed using UPFC, STATCOM, SSSC and other FACTS devices using conventional or intelligent techniques; most try to find their effect on the distance relay performance. But these works did not include the impact of UPFC location, fault impedance trajectories, fault locations, and fault resistance values. If included with these effects, the perfect intelligent design will give a fast clearing fault time.

3. The aim and objectives of the study

This study aims to design a new fuzzy distance relay that includes the impact of a unified power flow controller that changes the apparent impedance of the distance relay. This will make it possible to discover the faults and the relays not experiencing underreaching or overreaching.

To achieve the aim, the following objectives were set:

– to determine the new characteristics and impedance trajectories of the distance relay for various normal and fault conditions without and with using a unified power flow controller;

– to collect and save all resulting data and new characteristics as an input-output data set to use in designing the new fuzzy distance relay using MATLAB Neuro-Fuzzy Designer;

– to test the proposed fuzzy distance relay protection system for protecting and validating a system's efficacy.

4. Materials and methods

4. 1. Unified Power Flow Controller Operating Principles

UPFC can restrict the moment and direction of active power flowing in lines, as seen in equation (1), by relating the output voltage of voltage-sourced converter (VSC) as magnitude and the phase angle $V_3\angle\delta$ with AC voltage supply V_2:

$$P = \frac{V_2 V_3}{X}\sin\delta. \tag{1}$$

Therefore, as seen in equation (2), reactive power can also be controlled by controlling the correlating $V_3\angle\delta$ for $V_2\angle 0$, where the reactive power can be generated when $V_3>V_2$ and consumed when $V_3<V_2$:

$$Q = \frac{V_2^2}{X} - \frac{V_2 V_3}{X}\cos\delta. \tag{2}$$

Fig. 2 provides a schematic diagram of a UPFC. A shared DC connection from a DC storage capacitor was used to control the two VSCs that make up the UPFC, called "shunt" and "series" converters. The primary purpose of the operating shunt converter is to supply or absorb the actual power needed by the series converter at the shared DC connection. A transformer that is linked to the shunt then transforms the power from the DC link back into AC coupled to the transmission line. The shunt converter can also function as a synchronous condenser to produce reactive power for the AC system. Meanwhile, the series converter can exchange reactive power with the AC system and inject voltage, with regulated magnitude and phase angle in series with the transmission line, via a series transformer. It can also control active power flow in the transmission line [25].

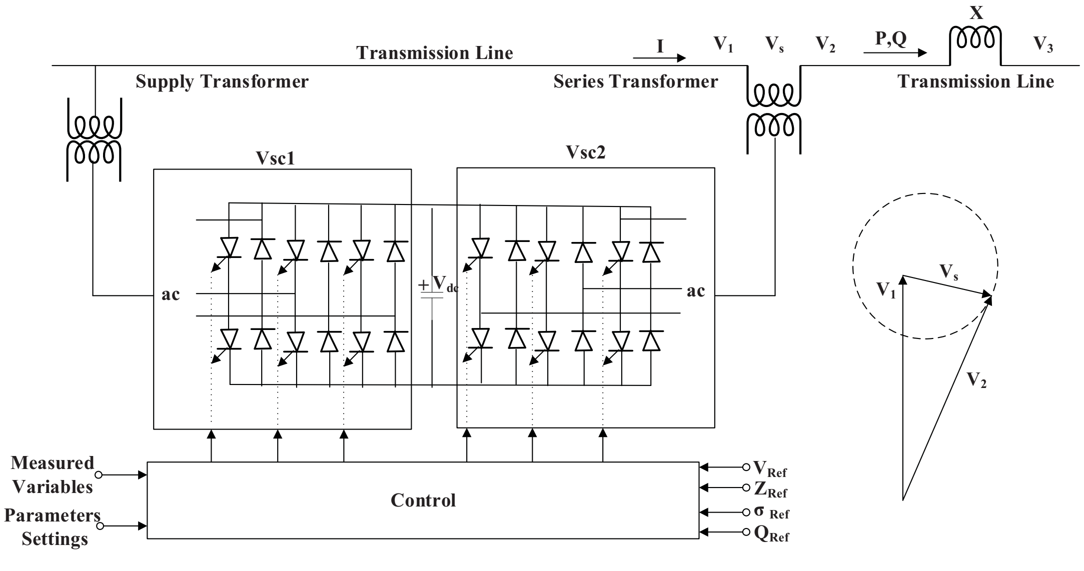


Fig. 2. A unified power flow controller with two voltage-sourced converters

As real power can now be transferred from the shunt converter to the series converter via the DC link, the FACTS design offers far greater flexibility in regulating the active power (P) and the reactive power (Q) of a line than the SSSC. Furthermore, unlike the SSSC, the injected voltage can now appear at any angle for the line current when they need to remain in quadrature with each other. As seen in Fig. 2, the end of V_2, where $V_2=V_1+V_s$, creates a circular locus when the amplitude of the injected voltage is kept constant and its phase angle with respect to V_1 is adjusted from 0 to 360 degrees. The phase shift and parameters of V_2 and V_3 at both line ends vary. Therefore, it may be possible to regulate both P and Q supplied at the end of one line. Fig. 2 shows the UPFC regulated zone as an area bound by an ellipse in the P-Q plane [3].

4. 2. Distance Relay

Distance relay (DR) protection offers protection and coherence in its most basic form. Its operation is determined by the distance between the relay site and the fault point [26]. The method of installing distance protection relays may differ between manufacturers. Therefore, it is common for two different distance protection relays to display entirely different settings while protecting the same power line. The graphical qualities may differ significantly as well. Therefore, relay manufacturers should disclose the relay settings needed to protect a standard power system, which would help users better understand the many relay setting philosophies. Fig. 3 shows the relay setting calculations [27].

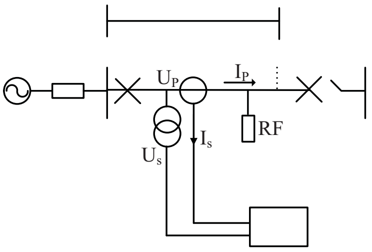


Fig. 3. Example of power system setting calculations

Quadrilateral operating characteristics are extensively used to provide distance protection in real power grids. Fig. 4 shows the resistive reach setting (R_{set}) and the reactive reach setting (X_{set}). In most cases, α_1 is between 15° and 30°, α_2 is between 15° and 30°, α_3 is between 60° and 65°, and α_4 is between 7° and 10°.

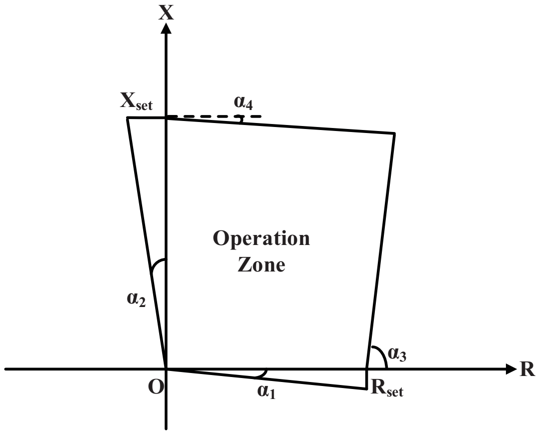


Fig. 4. Impedance relay with quadrilateral characteristics

If a fault occurs within the setting range of protection, the effective fault impedance (Z_f) will inevitably enter the functioning zone, regardless of whether the protection is activated [28].

4. 3. Unified Power Flow Controller Phasor-Type

A UPFC phasor-type was adopted using the powergui block-activated phasor simulation technique in the MATLAB®Simulink environment. It is possible to undertake faults analysis and stability studies on UPFC, including synchronous generators, motors, and dynamic loads, to examine how it influences electromechanical oscillations fundamental frequency transmission capacity. Fig. 5 shows a single-line diagram of a standard power system with a UPFC [29].

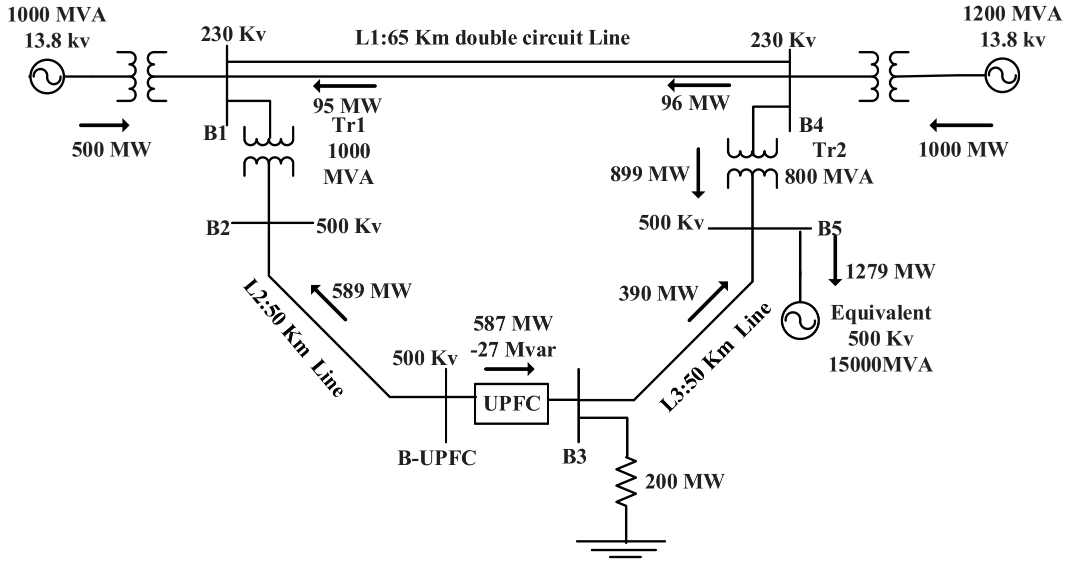


Fig. 5. A single-line diagram of a standard power system with a unified power flow controller

The prototype shown in Fig. 5 was used to design the system proposed in this work. A 500 kV/230 kV transmission system controlled the power flow using UPFCs. The loop-connected system consisted of five buses (B1 to B5), two transmission lines (L1, L2), 2*500 kV/230 kV transformers; Tr1 and Tr2; two power plants located on the 230 kV system generate a total of 1,500 MW. The generation plants included a speed governor, excitation control systems, and stabilizers. In typical operation, most of the 1,200 MW generation capacity of power plant #2 is exported to the 500 kV equivalent through 3*400 MVA transformers (T2). T2 was taken as 2*400 MVA as a contingency case. *P* and *Q* were controlled by the UPFCs located at the beginning, middle, and end of line L2. The UPFC consisted of two 100 MVA insulated gate bipolar transistor (IGBT)-based converters with a DC link connecting a shunt converter to a series converter. The maximum voltage that the series converter can inject into line L2 is 10 % of the nominal phase voltage (28.87 kV).

4. 4. Model System

This present study is divided into three parts. The first part, which examines normal operating conditions without faults, is divided into four scenarios:

1) Without a UPFC.

2) With a UPFC in the middle of the transmission line.

3) With a UPFC at the left side of the beginning of the transmission line.

4) With a UPFC at the end of the transmission line (Fig. 6).

The impedance trajectory of the four scenarios and faults are determined and plotted in the second part. Fig. 7 provides a flowchart of preparing the input-out data sets (*R*, *X*, out), where *R* and *X* are the apparent resistance and reactance, respectively, while the out is the trip signal.

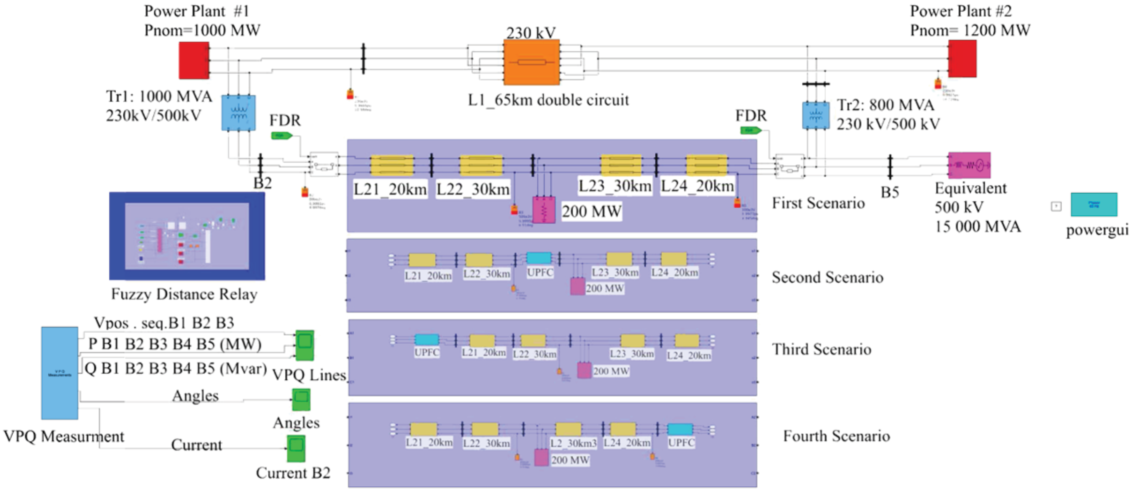


Fig. 6. The model system in MATLAB® Simulink for four scenarios

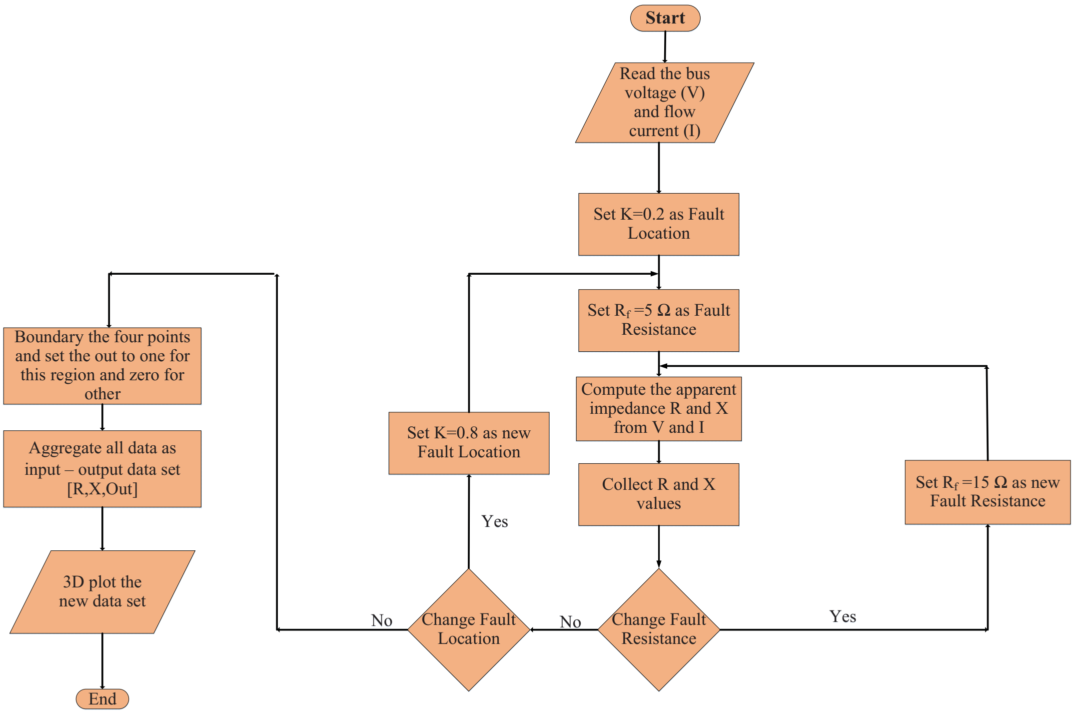


Fig. 7. Flowchart of preparing the input-output data set

As shown in previous Fig. 7, this research work was done at different fault resistance values R_f=5 Ω, R_f =15 Ω, and different fault locations *K*=0.2, *K*=0.8 for each fault resistance (R_f).

5. Results of designing a fuzzy distance relay without and with a unified power flow controller

5. 1. Distance relay characteristics and impedance trajectory with and without a unified power flow controller

In Fig. 8–11, distance relay characteristics were drawn with the impedance trajectory for three phases to a ground fault with different fault resistance values and locations for all four scenarios, where *K* is the fault location from L2 (*K*=0.2, *K*=0.8) and R_f is the fault resistance (R_f=5, R_f=15). Each rectangle relay characteristic was plotted according to the four *K* and R_f value points.

In this first, without a UPFC scenario, the impedance trajectory remained within the operating characteristics of the distance relay. Therefore, this relay will send a trip signal independent of any defect.

However, in the second, third, and fourth scenarios with UPFCs at different locations, the signal appeared under-reached when the same setting was used. Therefore, the characteristics of the relay had to be changed to include these new modified effects. Fig. 8–11 show the new features and fault impedance trajectories. The relay will send a trip signal without any problems.

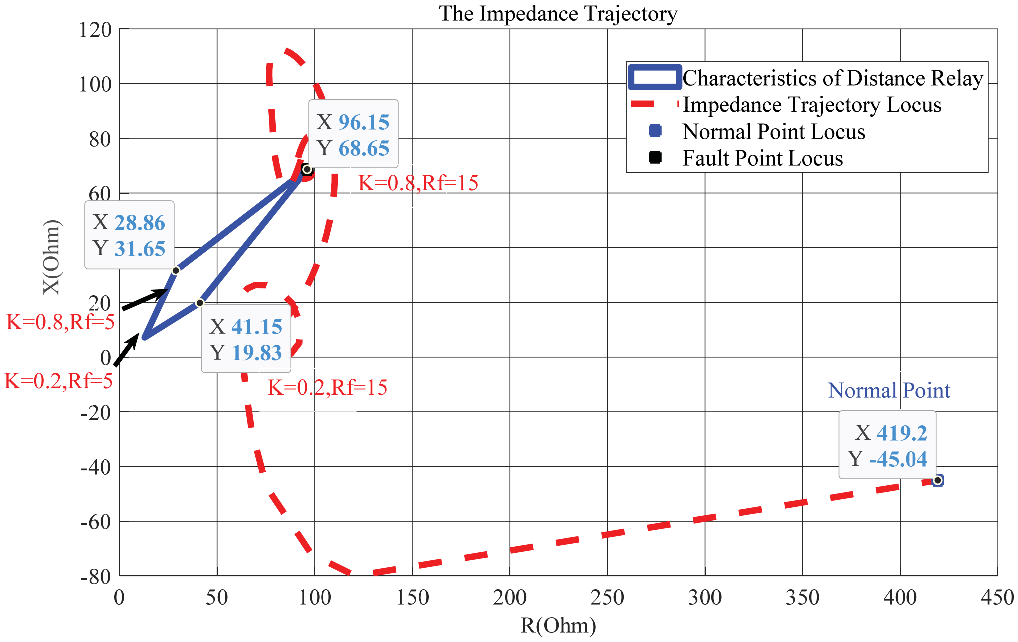


Fig. 8. Impedance trajectory of the first scenario, without the unified power flow controller

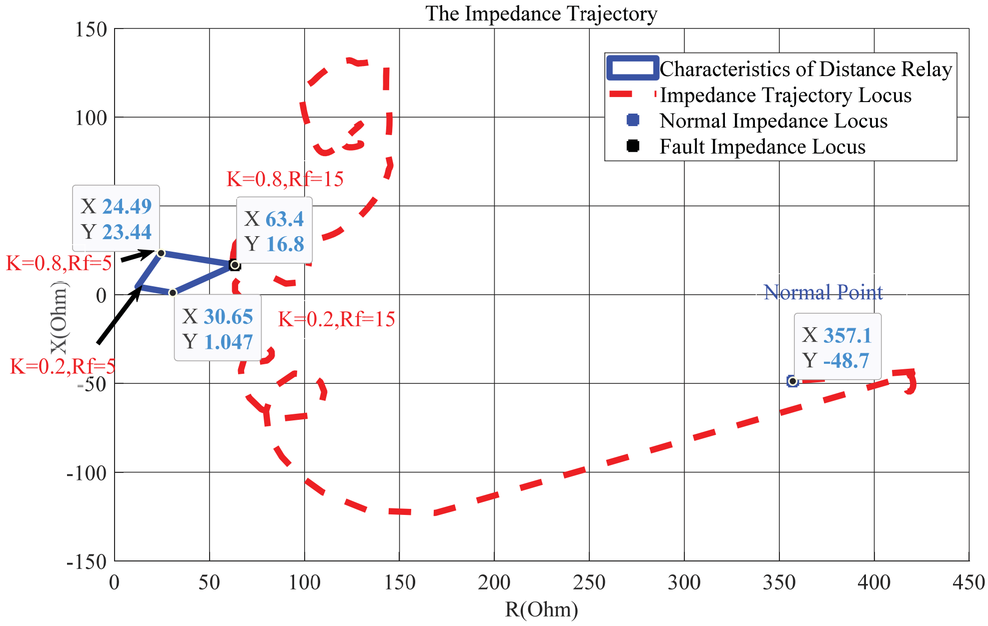


Fig. 9. Impedance trajectory of the second scenario, with the unified power flow controller at the middle of the transmission line

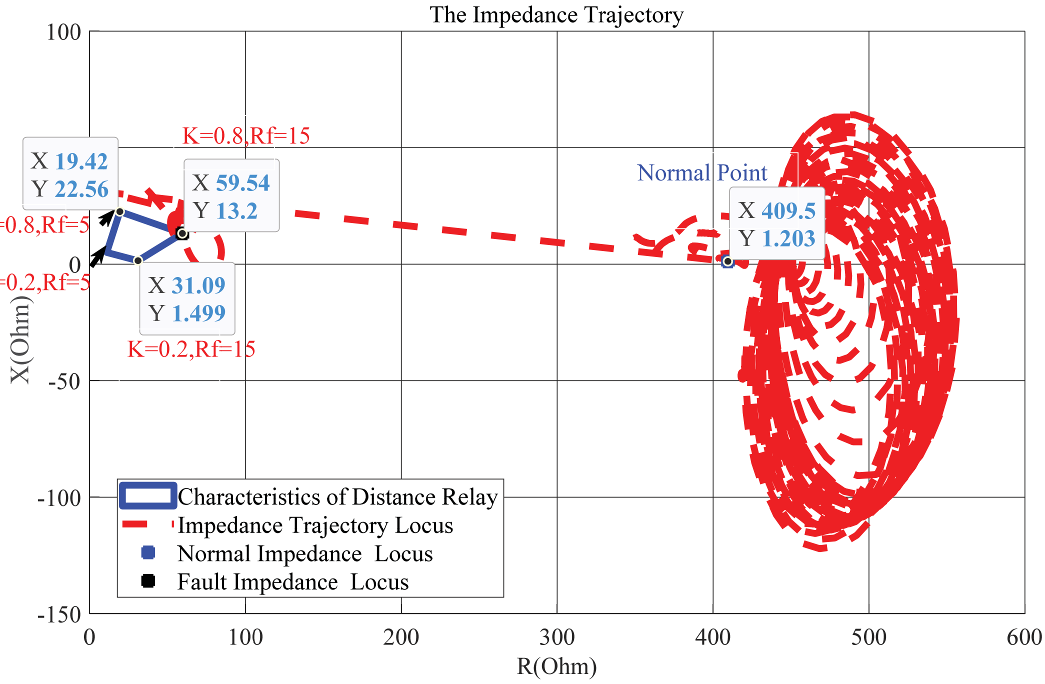


Fig. 10. Impedance trajectory of the third scenario, with the unified power flow controller at the beginning of the left side of the transmission line

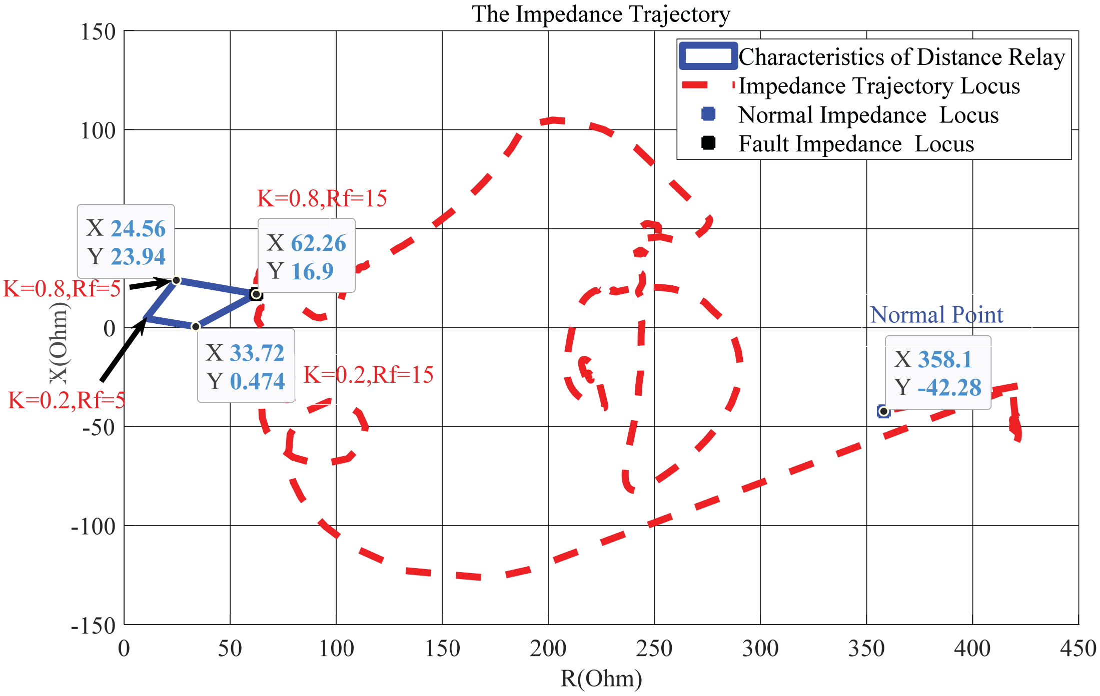


Fig. 11. Impedance trajectory of the fourth scenario, with the unified power flow controller at the end of the transmission line

The path of the impedance trajectory during fault for all scenarios starts from the normal operation point (no fault) to the end trajectory point. The end trajectory point must be in touch or inside the characteristic of the distance relay to operate. The long path occurs when UPFC is at the beginning of the transmission line.

5. 2. Designing the Fuzzy Distance Relay

As shown in Fig. 12, all the processes were used for collecting input-output data sets for the four scenarios. These data were used to design the proposed fuzzy distance relay (FDR) using MATLAB® Neuro-Fuzzy Designer.

Fig. 13, 14 show the new FDRs, and Fig. 15 displays the three-dimensional FDR characteristics for each scenario.

The three-dimensional FDR characteristics for each scenario displayed in Fig. 15 explain the differences in the characteristics. The shape of the scenario without UPFC shows the largest area and rotation for the characteristics compared to using UPFC.

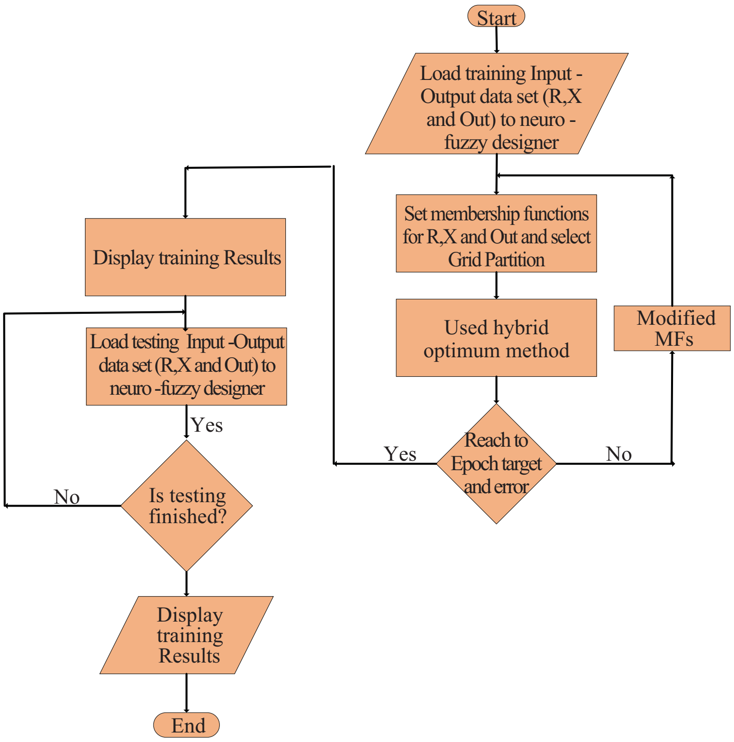


Fig. 12. Flowchart of designing the fuzzy distance relay

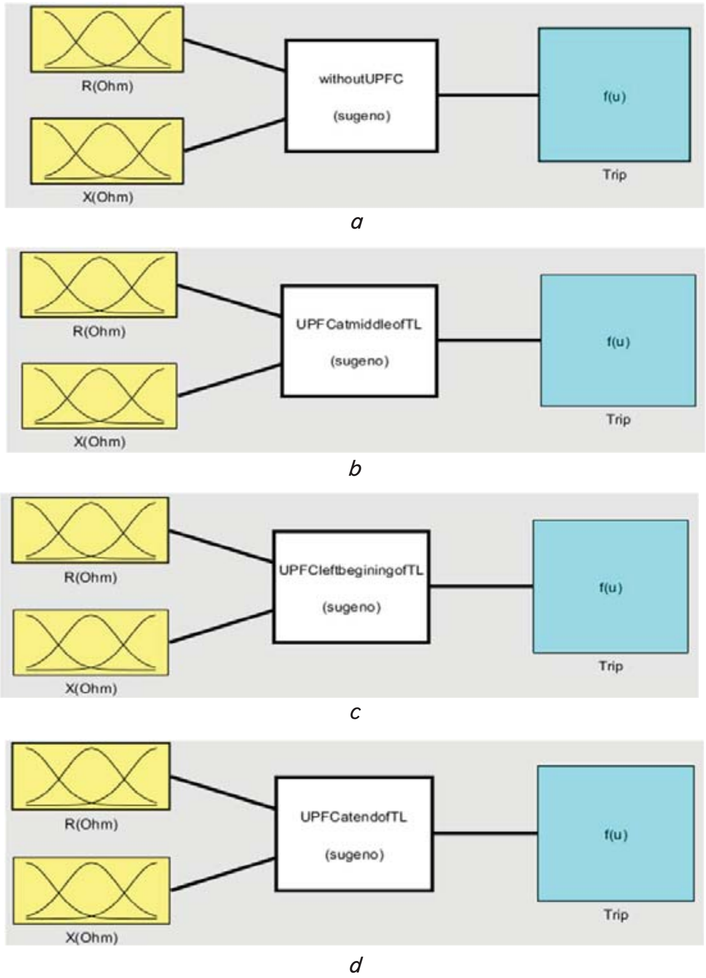


Fig. 13. The fuzzy logic of the four scenarios: *a* — without a unified power flow controller; *b* — with a unified power flow controller at the middle of the TL; *c* — with a unified power flow controller at the left side of the beginning of the transmission line; *d* — with a unified power flow controller at the end of the transmission line

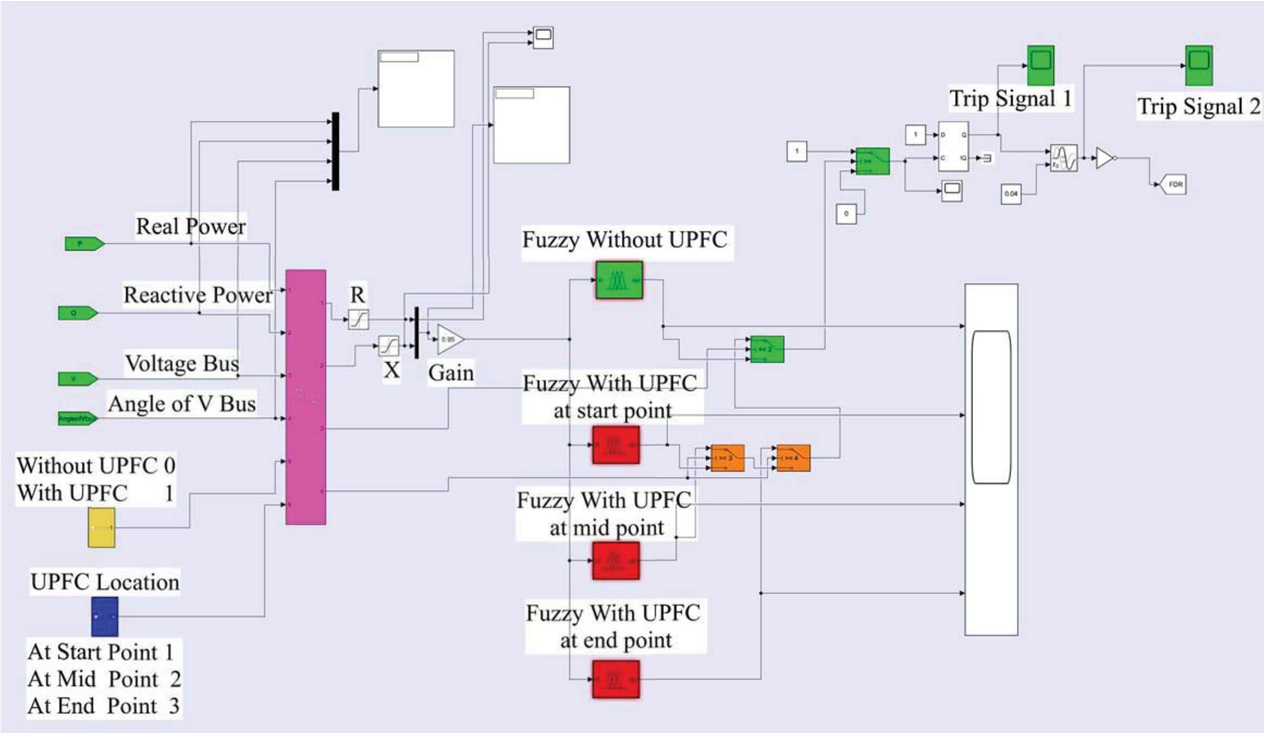
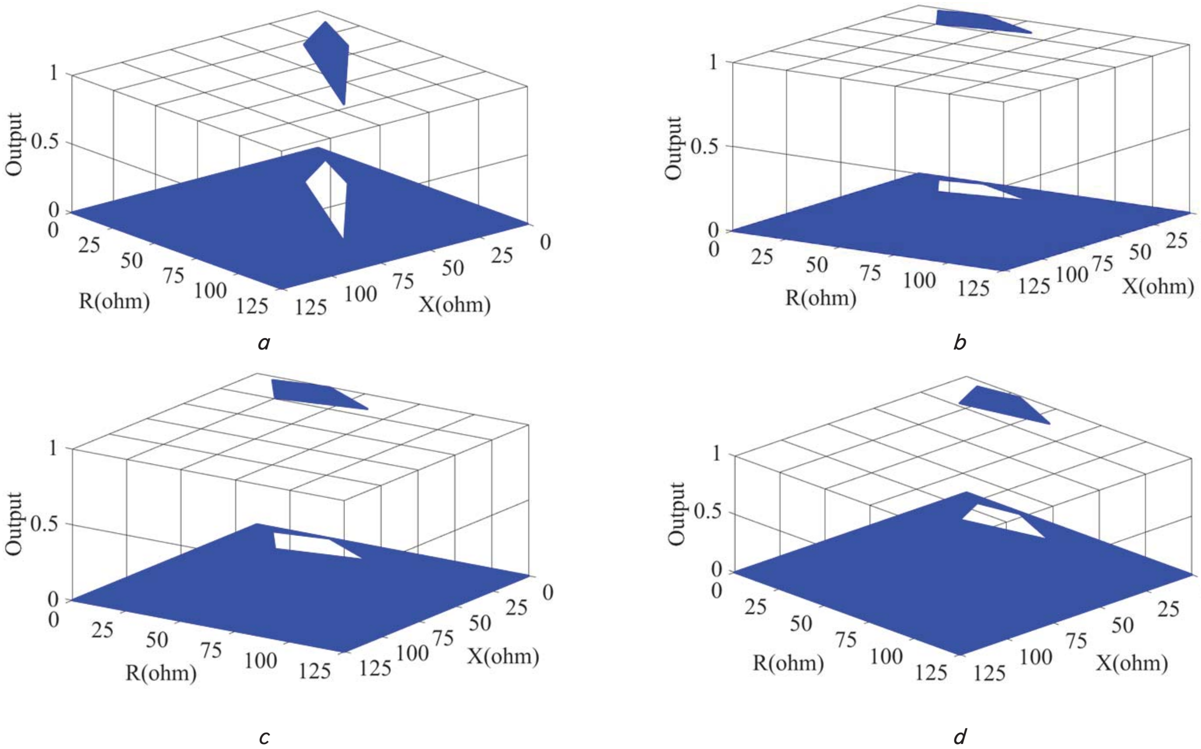


Fig. 14. Fuzzy distance relay (FDR)



a

b

c

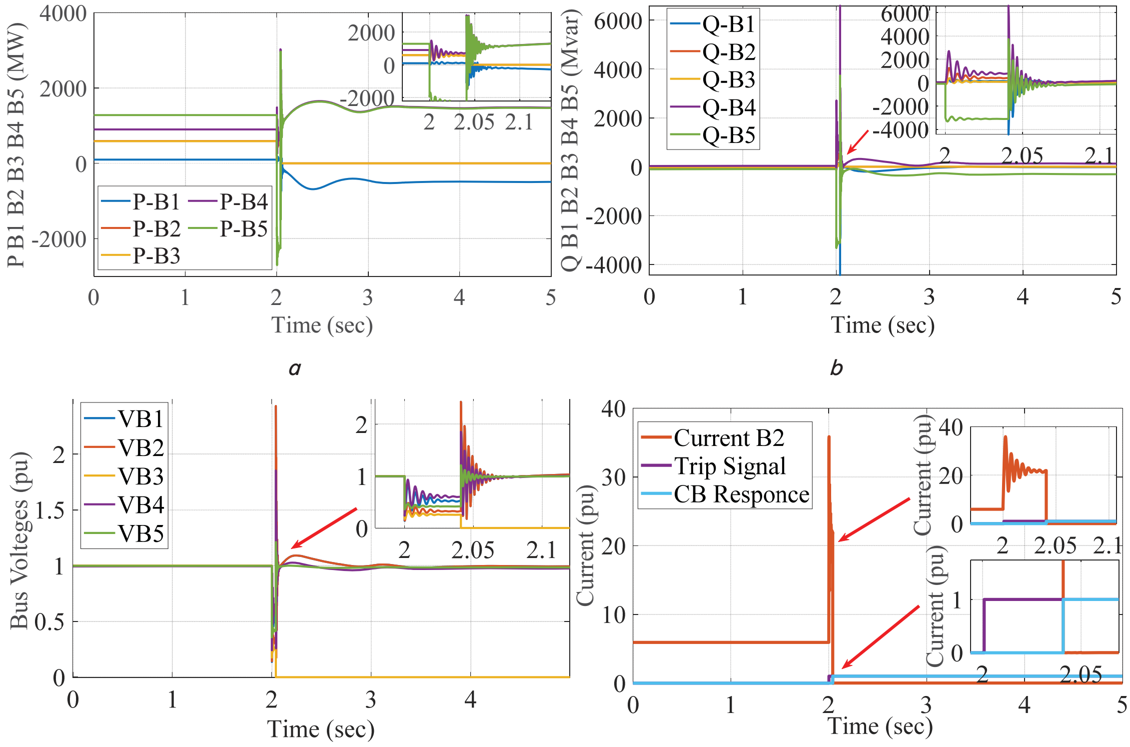
d

Fig. 15. Three-dimensional fuzzy distance relay characteristics for the four unified power flow controller location scenarios: *a* – without a unified power flow controller; *b* – with a unified power flow controller at the middle of the transmission line; *c* – with a unified power flow controller at the left side of the beginning of the transmission line; *d* – with a unified power flow controller at the end of the transmission line

5. 3. Testing the Proposed Protection System

The proposed protection system in Fig. 14 was tested, as displayed in Fig. 16–21 where the figures show the fast responses of the FDR for all four scenarios described.

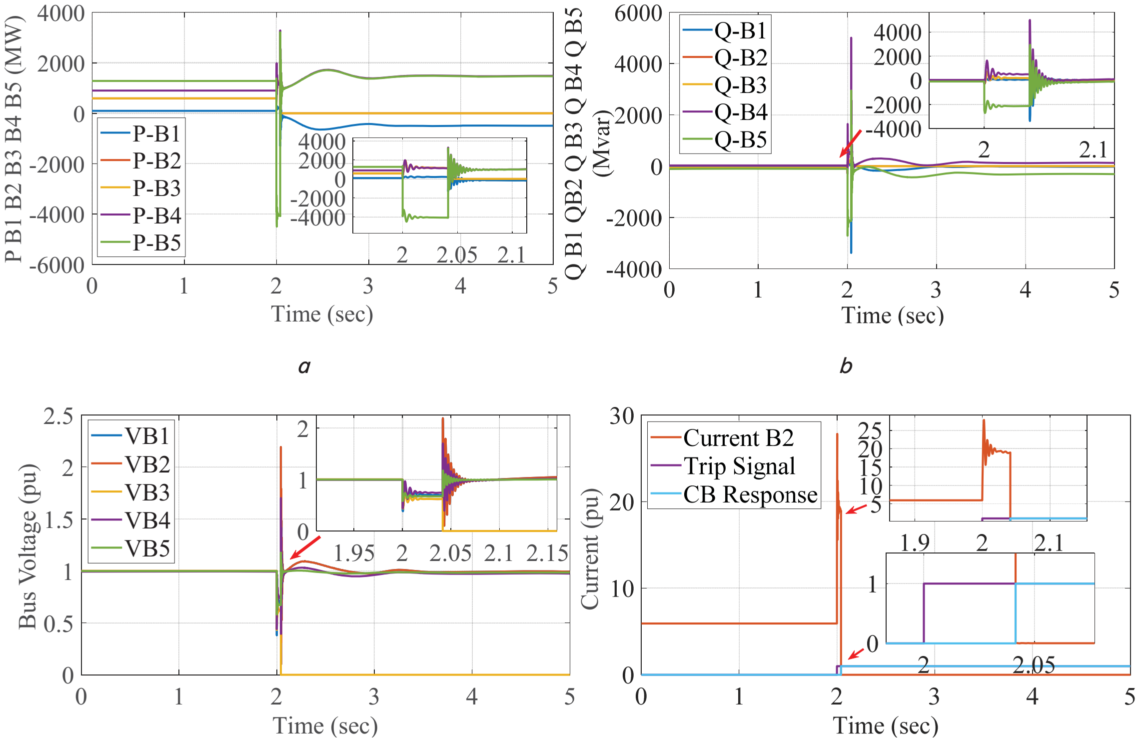
All the above tests with UPFC were done during the UPFC operation, depending on the conditions shown in Table 1. All the reference values change within the rating of UPFC depending on time.



a *b*

c *d*

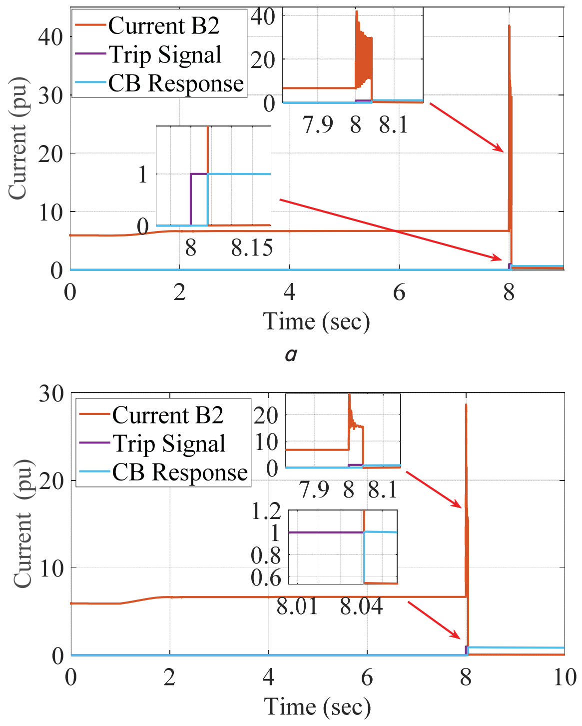
Fig. 16. The first scenario response with R_f=5 Ω:
a — real power (P); *b* — reactive power (Q);
c — bus voltage (V); *d* — current (I)



a *b*

c *d*

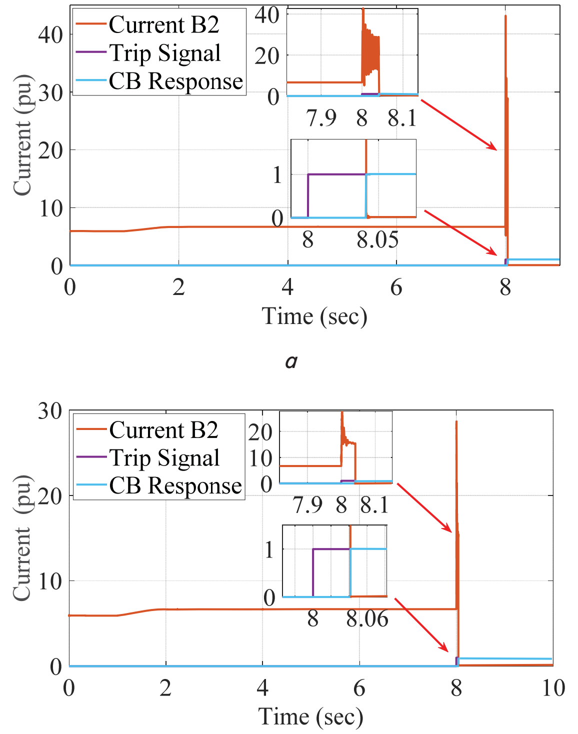
Fig. 17. The first scenario response with R_f=15 Ω:
a — real power (P); *b* — reactive power (Q);
c — bus voltage (V); *d* — current (I)



a

b

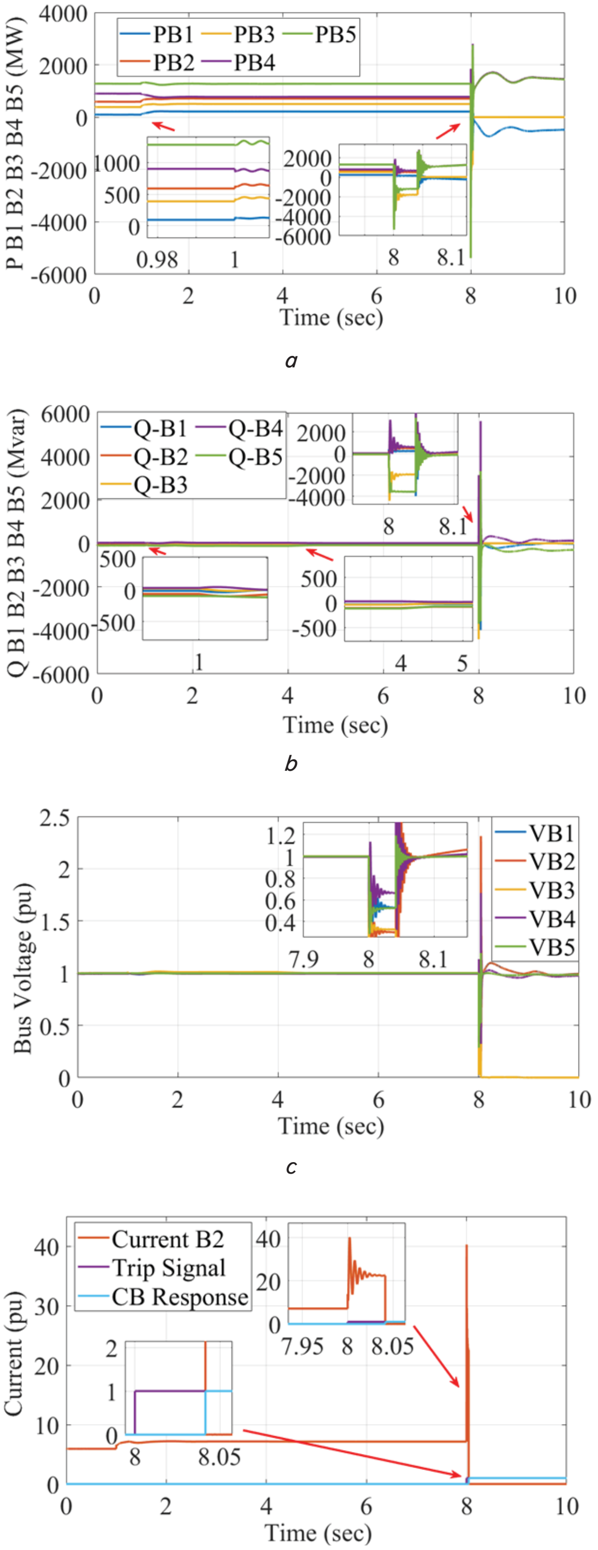
Fig. 18. Fault currents with fuzzy distance relay response for a unified power flow controller at the middle of the transmission line, third scenario response: *a* – R_f=5 Ω; *b* – R_f=15 Ω



a

b

Fig. 19. Fault currents with fuzzy distance relay response for a unified power flow controller at the left side of the beginning of the transmission line, third scenario response: *a* – R_f=5 Ω; *b* – R_f=15 Ω



a

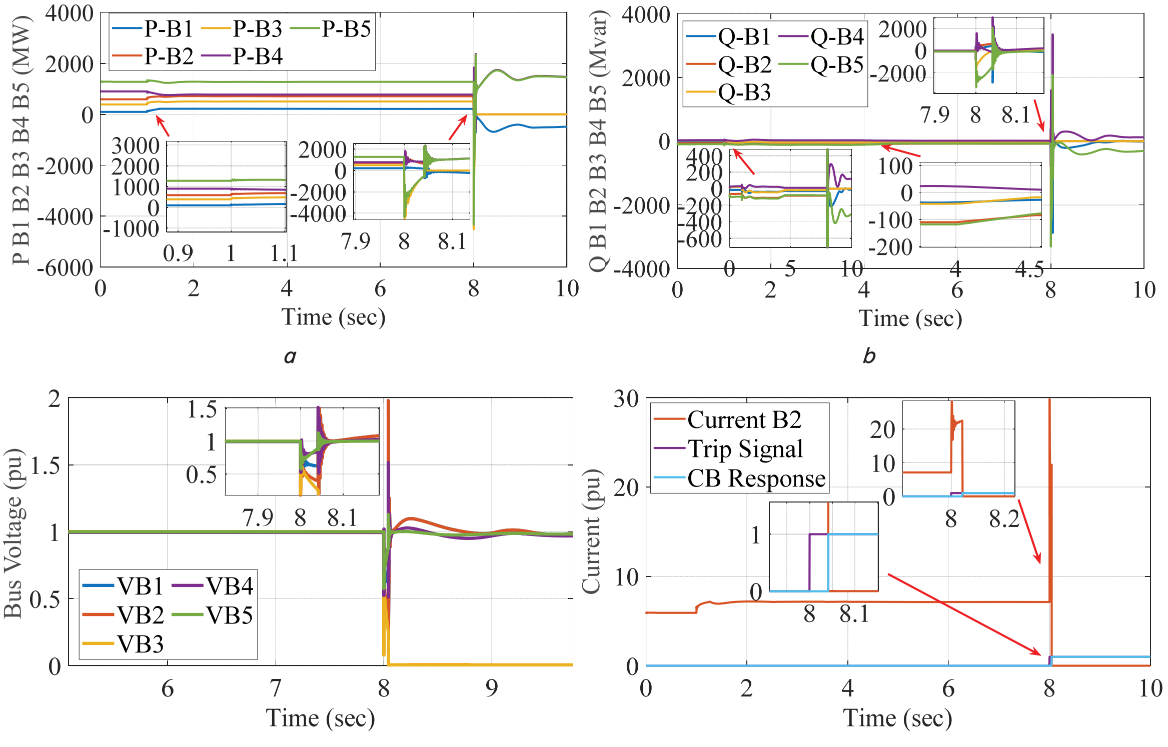
b

c

d

Fig. 20. The fourth scenario response with R_f=5 Ω using the unified power flow controller at the end of the transmission line: *a* – real power (P); *b* – reactive power (Q); *c* – bus voltage (V); *d* – current (I)

As shown in Table 1, the change in UPFC settings affects the voltage magnitude and the angle of the inserted voltage resulting in a change in the power flow of the transmission line.



a

b

c

d

Fig. 21. The fourth scenario response with R_f=15 Ω using the unified power flow controller at the end of the transmission line: *a* — real power (P); *b* — reactive power (Q); *c* — bus voltage (V); *d* — current (I)

Table 1

Reference UPFC operation values

Time (sec)	P_{ref} (p.u.)	Q_{ref} (p.u.)	Series voltage (V)	Angle of the series voltage (Degree)
0	5.87	–0.27	9.4e-3	90
1	6.6	–0.27	0.06	93
4	6.6	+0.27	0.07	80

6. Discussion of the Response Results of the Fuzzy Distance Relay

The results were divided into three sections.

Firstly, the apparent impedance of the distance relay will change if a fault occurs, as seen in Fig. 8. It also varies differently if a UPFC is added with a fault occurring. The apparent impedance also depends on the location of the UPFC. Fig. 9–11 show the impedance trajectories of adding UPFCs in different places. New distance relay settings were calculated and plotted to manage these changes. As seen, the relays did not experience underreaching or overreaching.

Secondly, the new characteristics were used as the input-output data sets to create fuzzy systems for each scenario. Fig. 14 depicts FDR that was designed. The inputs were the voltage signal, current signal, presence or absence of UPFC and its location. The output was one signal sent to the circuit breaker if a fault occurred.

The first difficulty is that a large amount of data will be generated. So, the proposed relay design contains four fuzzy systems to overcome this problem (Fig. 14), selected depending on the relay setting. This way avoid, the complexity in calculation and errors in the decision may occur.

Thirdly, the designed Fuzzy Distance Relay (FDR) was tested in the system with and without a UPFC at different locations with the reference operation values shown in Table 1. The obtained results of UPFC step responses in normal conditions were compared and compatible with the paper [29]. Fig. 16–21 show that the fault response was good as all faults were discovered, and a tripping signal was sent in approximately 14.2 milliseconds, which is less as compared to the reference [30], which used a neuro-fuzzy inference system (ANFIS) and reference [13], which used an adaptive relay. As the circuit breaker had a delayed mechanical response of 40 milliseconds, the total fault-clearing duration was less than 54.2 ms.

The peculiarities and main feature of the proposed FDR is the ability to discover and distinguish faults in any system containing UPFCs devices despite the UPFC playing a role in changing the apparent impedance of the distance relay.

The limitation of this study is that fault resistance (R_f) is adopted in only two values (5 and 15 ohms). Also, there are three general limitations for this type of protection system; the distance relay does not have the capability to determine if the fault originates from the inside or the outside protective zone; also, there is a limitation placed on the fault resistance's capacity for measurement; and variations in power swings indicate that there is an impact being felt by the distance relay performance if the UPFC is not used.

This study solves only the problem of the impact of UPFC on the distance relay; further work may consider adding the characteristics of the other FACTS devices to the proposed FDR.

7. Conclusions

1. The shape of quadrilateral polygon characteristics of the distance relay can be concluded from determining the four-point values depending on K and R_f for different fault conditions. The impedance trajectories were added to these shapes to test them. When a UPFC was added, these characteristics were changed. The location of the UPFC (mid, beginning, and end of the transmission line) also affects these characteristics by rotating and modifying the quadrilateral polygon shape. The impedance trajectories also change under these conditions, where the long path occurs when the UPFC is located at the beginning of the transmission line.

2. UPFC can be cases of maloperation, which changes the apparent impedance of distance relays. So, the proposed FDR included this effect. Any delay or fault un-clearing may cause system instability, which is the primary cause of large-scale blackouts. Four scenarios, one without a UPFC and three with a UPFC in different locations, were developed to collect the input-output training data set to create the FDR in MATLAB® Neuro-Fuzzy Designer. The collected data gives other characteristics for these scenarios, where the first scenario (without using UPFC) has the largest characteristic area. In contrast, it has the smallest area for the third scenario (UPFC located at the beginning of the transmission line).

3. The newly-organized characteristics were tested at varying impedance trajectories and indicated good response with a trip signal time of approximately 1.42 ms. UPFC works on damping or reducing power swings due to faults or any sudden disturbance in the power system, so UPFC with the FDR protection system will increase the system's reliability. UPFC working under normal conditions (Table 1) was not affected by the proposed FDR.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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