An Adaptive Neuro Fuzzy Inference System based Method for DC Fault Recognition in VSC-MTDC System

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Abstract— **This paper presents an Adaptive Neuro Fuzzy Inference System (ANFIS) method for recognizing the fault in a Voltage Source Converter-Multiterminal HVDC (VSC-MTDC) system. A four-terminal VSC-based HVDC system is designed in MATLAB software and used for the validation of research. The proposed scheme has advanced features that overcome the limitations of a fuzzy inference system, as it does not need an expert to provide the best performance. Artificial Neural Networks (ANNs) depend only on input and output data through the training process. ANFIS is a very effective method that combines the strengths of artificial neural networks (ANN) in learning from processes and the ability of fuzzy inference systems to deal with uncertain input. In order to protect against faults, two distinct FIS models have been developed to recognize pole-to-ground and pole-to-pole faults. The results indicate a trip signal when a fault is present, hence increasing the reliability of the system. This approach provides quick outcomes without taking any feedback from the remote end of the system**.

Index Term: **Adaptive Neuro-Fuzzy Inference System, DC Fault Recognition, VSC-MTDC Systems.**

I. INTRODUCTION

Raising demand for energy and, consequently, an increase in the transmission network's power transmission capacity are major factors contributing to the development of traditional technology. The growing need for electrical energy is directly correlated with the development of transmission infrastructure. Power system performance declines as transmission networks get bigger and more complex because of issues with voltage quality, load flow, and power oscillations. Some efficient ways to satisfy these requirements are provided by High-voltage direct current (HVDC) technologies and flexible AC transmission systems (FACTS). In recent years, HVDC technology has been seen as an attractive choice in India to enhance the capacity of power grid distribution [1]. There are several HVDC transmission projects that are either planned or under construction. System reliability can be increased by utilizing HVDC technologies in the power system. Complementary technologies are FACTS and HVDC. When transferring electrical power in large quantities, an HVDC system uses direct current (DC). Large-scale transmission and distribution networks are the result of advancements in polyphase circuit design, the accessibility of transformers, and the use of induction motors and other AC equipment.

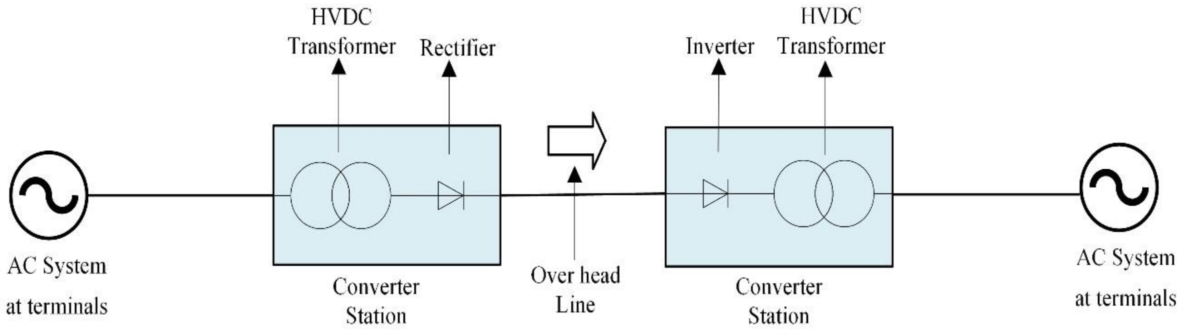

Fig.1. HVDC transmission system layout.

Why is HVDC Preferred over the HVAC transmission line?

1. When it comes to long-distance efficiency, HVDC transmission beats HVAC transmission. Since DC lines have less resistance and lose less reactive power than AC lines, power can be transported over thousands of kilometers using HVDC and with reduced losses. Because of this, HVDC is especially well suited for connecting remote hydropower plants or offshore wind farms to major population areas.
2. Transmission losses are reduced in HVDC transmission lines when compared to HVAC lines. The primary reason for this is that DC transmission results in fewer reactive power losses and no skin effect. HVDC is, therefore, more energy-efficient, which lowers the need for power generation and lowers utilities' operating expenses.
3. When compared to HVAC systems, HVDC systems offer better controllability and stability. Precision control over voltage regulation, frequency stability, and the flow of both active and reactive power is possible with HVDC converters. In networked AC systems with different loads and generation patterns, in particular, this enables operators to dynamically modify power flow and preserve grid stability.

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4. By using HVDC technology, asynchronous AC grids that operate at various frequencies or with phase variations can be connected more easily. Grid dependability is improved, and regional energy sharing is encouraged via HVDC systems, which convert AC to DC and back to AC to facilitate smooth power exchange between grids with incompatible characteristics.
5. Compared to older Line Commutated Converter (LCC) HVDC systems, modern HVDC systems use Voltage Source Converter (VSC) technology, which has several benefits. VSC-HVDC systems offer autonomous control over the flow of active and reactive power, as well as quick response times and enhanced transient stability. In the event of a blackout, VSC-HVDC systems can also function in a black-start mode, which speeds up the restoration of grid operations.

In 1954, ABB offered the first commercial HVDC connection in history. This link, which ran at 100 kV and had a 20 MW capacity, linked the Swedish mainland to the island of Gotland. With a distance of 2071 km, the Xiangjiaba-Shanghai HVDC link now holds the record for being the longest in the world. It runs at an 800 kV DC voltage and has a 6400 MW power rating. HVDC transmission has gained traction in India in recent years as a possible planning tool to increase the grid's capacity and supply while fixing known network issues. One of the few countries actively engaged in the design, development, and commissioning of a large number of high-voltage direct current (HVDC) systems is India [2]. The most recent information on India's HVDC system is included in Table I [3].

TABLE I
HVDC System in India

S.No	Name of Project	Established by	Commissioned year	Power Rating	DC Voltage	Type of HVDC	Length of line
1.	Vindhyachal	PGCIL	1989	2x250 MW	70 KV	Back To Back	NA
2.	Rihand-Dadri	PGCIL	1991	1500 MW	500 KV	Bipole	816 Km
3.	Chandrapur	PGCIL	1997	2x500 MW	205 KV	Back To Back	NA
4.	Chandrapur-Padghe	MSEB	1999	1500 MW	500 KV	Bipole	752 Km
5.	Sasaram	PGCIL	2002	1x500 MW	205 KV	Back To Back	NA
6.	Talcher-Kolar	PGCIL	2003	2000 MW	500 KV	Bipole	1369 Km
7.	Gazuwaka	PGCIL	2005	2x500 MW	205KV /177KV	Back To Back	NA
8.	Ballia-Bhiwadi	PGCIL	2010-11	2500 MW	500 KV	Bipole	780 Km
9.	Mundra-Mohindergarh	APL	2012	1500 MW	500 KV	Bipole	986 Km
10.	Bishwanath-Agra	PGCIL	2015	6000 MW	800 KV	Multi-Terminal	1728Km

I.I. INTRODUCTION OF MTDC SYSTEM

A Multiterminal High Voltage Direct Current (HVDC) system, often abbreviated as MTDC, is a configuration of HVDC transmission that has more than two converter stations, some of them operated as rectifiers and others as inverters. Unlike traditional point-to-point HVDC systems, which connect only two terminals, MTDC systems allow for the simultaneous transmission of power between multiple locations. An efficient method of constructing an MTDC system from an existing two-terminal system is to insert tappings. The simultaneous functioning of converters and bipoles can alternatively be seen as a multiterminal operation. Future prospects of MTDC include:

1. The implementation of power distribution systems on automobiles.
2. The structural framework of a microgrid.
3. Integration of offshore wind energy
4. Large-scale integration and transmission of renewable energy.
5. AC islanding refers to the process of dividing an AC system into smaller segments.

The limitations of traditional HVDC systems include their susceptibility to commutation failure, inability to reverse the direction of current flow, and the need for active network connections at both ends. VSC-HVDC, a more recent addition to the high-voltage technology sector, has successfully eliminated all the cited limitations of classical HVDC. The development of a multiterminal HVDC (MTDC) system has drawn attention. Voltage Source Converter-based Multi-Terminal DC (VSC-MTDC) systems have attracted considerable interest because of their ability to facilitate efficient long-distance power transfer[4]. These systems address critical needs in electrical engineering by facilitating the integration of renewable energy, enhancing grid stability and reliability, increasing power transfer capability, interconnecting asynchronous AC grids, providing controllability and flexibility, and delivering economic benefits to power systems worldwide. In MTDC systems, fault detection plays a critical role in quickly detecting abnormal conditions like short circuits or faults on the DC lines or converter stations. Precise fault detection can be accomplished by employing a range of approaches, including voltage-based protection, travelling wave protection, and current-based protection. When a fault is detected, the protective system needs to separate the faulty part of the MTDC system to avoid more harm and ensure the stability of the system.

There are various fault detection methods used in HVDC systems, like ANN, fuzzy inference systems, machine learning approaches, Maximum Overlap Discrete Wavelet Transform (MODWT) [5], etc. Multi-location faults can be detected and classified by applying the DWT-ANN approach [6]. The fuzzy-based direction relaying technique is also applicable in other types of compensated transmission systems other than the HVDC system [7]. The multiterminal VSC-HVDC system employs many techniques, including the utilization of the fast Fourier transform to analyze high-frequency components and track the change rate of the DC reactor voltage with pre-defined protection voltage thresholds [8], [9]. These approaches aim to quickly and precisely detect DC faults. An alternative protection technique employs a local measurement-based algorithm to detect faults in an MTDC system, specifically focusing on parameters such as overcurrent, under-voltage, rate of change of current, and rate of change of voltage [10]. Artificial Neural Networks (ANN) and Fuzzy Inference system-based approaches are also utilized in a multiterminal VSC-based HVDC system [11],[12]. All of the mentioned techniques were utilized to locate and recognize defects in the DC system, including faults between the pole and ground, as well as faults between poles. Using signal decomposition, the VSC-MTDC system was able to identify DC faults in a wavelet-based protection method [13]. The single-ended safeguards in a multiterminal VSC-HVDC grid are covered in the paper. These defenses include current differential protection, directional pilot protection, transient variable-based protection, and travelling wave protection [14]. Pole-to-pole fault detection using short circuit fault current estimates is also covered in the independent study in paper [15]. According to the converter application, the HVDC system makes use of a modular multilevel converter (MMC) construction, which has particular advantages when assessing the modulation approach. A machine-learning method is used to examine and identify DC faults from both pole-to-ground and pole-to-pole. A single-ended fault detection strategy based on support vector machines (SVMs) is employed in this method [16]. To assess DC pole-to-ground and pole-to-pole faults, the trigger criteria technique is used by the MMC-based MTDC system. This technique employs median absolute deviation for transient signal detection and depends on the voltage across the DC fault-current-limiting reactor [17], [18]. In order to conduct a separate study of pole-to-ground problems and to provide a protection strategy, the article addresses the development of a communication-based system [19].

The fuzzy inference system is inherently limited in that it lacks expertise on its own. Indeed, it requires the expertise of a specialist to optimize it and ensure optimal performance. Hence, in the case that a person with power assigns incorrect rules, the fuzzy logic controller may exhibit poor performance or make an incorrect conclusion. To address the constraints of a fuzzy logic controller, an artificial neural network can be employed to enhance the expertise of the fuzzy inference system. The artificial neural network (ANN) acquires knowledge of the system's behaviour by analysing input and output data. It then utilises the appropriate rules and assigns accurate membership function values to achieve optimal performance. ANFIS, among ANN, FIS, and ANFIS, is the most simple and precise technique that yields the most accurate results. The study has already examined the control and fault identification of the converter in an ANFIS-based HVDC system[20].

Fault detection in a multiterminal HVDC system is more challenging than in a conventional two-terminal HVDC system, as when the fault is incepted in an MT-HVDC system, the fault current is contributed by different remote terminals that are interconnected to remote sources, thus posing difficulty in fault detection by protection scheme based on measurements of the single terminal only. Furthermore, locating faults in an MTDC system is more complex due to the multiple paths for current flow as compared with point-to-point HVDC. In MTDC systems, isolating only the faulty section without disrupting the entire network is crucial. This requires sophisticated protection devices and schemes. This paper focuses on DC pole-to-ground and pole-to-pole faults, which are associated with both point-to-point HVDC and MTDC systems. DC faults propagate faster than AC faults, necessitating ultra-fast protection mechanisms to detect and isolate faults before they cause significant damage.

The use of ANFIS in a multiterminal HVDC system is the goal of this work. Thus, all that is required is a basic comprehension of artificial neural networks (ANN) and fuzzy inference systems, together with their hands-on implementation using MATLAB. In this study, a four-terminal High Voltage Direct Current (HVDC) system's faults are found using the Adaptive Neuro-Fuzzy Inference System (ANFIS). In a matter of milliseconds following the onset of the problem, the implemented technique detects the presence of a defect and promptly sends the trip signal to the system's control unit. The following makes up the structure of the paper: The design of the example system is shown in Section II. The recommended method that makes use of the ANFIS technology is described in Section III. In Section IV, the simulation work's outcomes are displayed. A comparison is given in Section V, and the paper's conclusions are wrapped up in Section VI.

II. VSC-MULTITERMINAL HVDC (MTDC) SYSTEM

The voltage source converter (VSC) is a crucial technology in the field of HVDC transmission. In classical HVDC systems, conventional thyristor devices can only control the turn-on process. The turn-off process is dependent on the current reaching zero, based on the specific conditions of the system and circuit. Both turn-on and turn-off can be employed to create self-commutated converters in conjunction with specific semiconductor devices, such as insulated gate bipolar transistors (IGBT). The DC voltage in these converters is typically fixed and remains constant due to the presence of a high capacitor that smooths out the voltage. As a result, an HVDC converter that uses IGBTs is commonly known as a voltage source converter. Possible categorization of HVDC converter:

1. Line-commutated converters (LCC) utilize switching devices, such as "thyristors," and are commonly seen in classical HVDC systems.
2. Self-commutated converters utilize high-speed switching devices like "IGBT" in VSC-HVDC systems.

Why is VSC preferred over LCC?

An inherent drawback of HVDC systems employing line-commutated converters is their need for reactive power. Irrespective of the direction of active power flow, the converter continuously consumes reactive power due to the lag between the alternating current entering it from the AC system and the alternating voltage. This results in the converter operating in a manner that is comparable to a shunt reactor. Furthermore, while functioning in the inverter mode, it sporadically has issues with commutation. In order to perform commutation, these converters require a synchronous voltage source of sufficient strength. A voltage source is not essential for the VSC to operate effectively. Due to pulse width modulation (PWM), the frequency spectrum of the converter output is altered, making harmonic filtering in VSC much less complex.

A. Voltage Source Converter (VSC)

In a voltage-sourced converter, the direct current exhibits bidirectional flow, demanding the use of bidirectional converter valves. The turn-off devices do not require the ability to reverse voltage, as the DC voltage remains constant and does not change direction. Devices like this that turn off in an unequal manner are known as asymmetric turn-off devices. Therefore, an asymmetric turn-off device, like a gate turn-off, combined with a reverse-connected parallel diode constitutes a voltage-sourced converter valve. Voltage source converters reverse the flow of current to reverse power, while maintaining the constant polarity of DC voltage. The following are the advantages of voltage source converters:

1. No commutation problem due to IGBT switches.
2. Fast commutation between terminals and no need for control.
3. Used in offshore power plants to supply and receive power.
4. Power reversal does not require voltage reversal, so it is best for MTDC systems.

Since VSC-based HVDC systems are modular by nature, scaling and expansion are made simpler. In a multi-terminal VSC-HVDC system, every converter station can function independently, allowing for the addition or removal of terminals as needed without materially affecting the operation of the system as an entire. There is less need for complex harmonic filtering equipment when using VSC-based converters since they produce less harmonic distortion than LCC-based converters. This reduces the complexity of multi-terminal HVDC system design and operation and lowers installation and maintenance expenses.

B. Four Terminal VSC-HVDC System

To examine and assess the behaviour of a mutli-terminal HVDC system (MTDC) under both normal and fault conditions, we have selected a four-terminal VSC-HVDC system as a representative sample [27, 28]. All four transmission lines in the sample system, namely Line 1, Line 2, Line 3, and Line 4, have a length of 200 km each. The simulation parameters of the sample system are displayed in Fig. 2. The modelling of transmission lines involves the utilization of the Pi section in combination with an 8 mH smoothing reactor connected in series. This transmission line will be used to transfer power between four identical AC systems. The neutral point clamped topology is used to model the voltage source converter (VSC) in both rectification and inversion applications. In order to accomplish this, a three-level output voltage is produced by utilising power electronic components such as diodes and IGBTs. The VSCs' power switches are actuated by applying sinusoidal pulse width modulation (SPWM) signals to the switches' gate terminals. The SPWM signal is generated by comparing the 1350 Hz carrier signal with the reference fundamental frequency of the signal, which is 50 Hz. Both the leakage reactance of the transformer and the reactance of the converter have a value of 0.15 per unit. Voltage Source Converters (VSCs) in High Voltage Direct Current (HVDC) systems possess the ability to regulate and manipulate both the active power (real power) and reactive power (imaginary power). The incorporation of DC capacitors in VSCs has led to a decrease in voltage fluctuations and the burden on reactive power in the DC component of the tested system, as indicated by the increased ratings. The effectiveness of the suggested method is simulated through modification of the two-terminal HVDC system depicted in Fig. 1. The results of the proposed approach are assessed using this sample system.

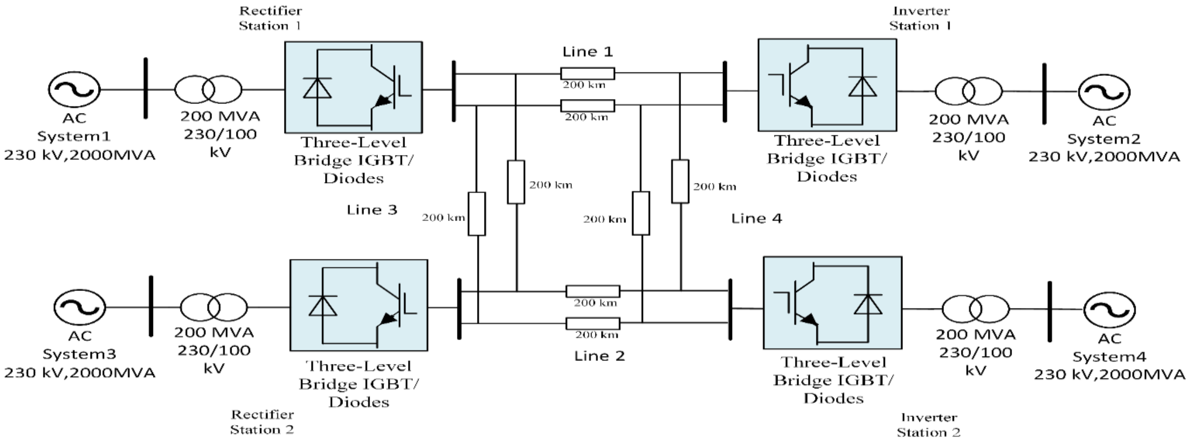


Fig.2. The Sample Four Terminal VSC-HVDC System.

C. *Types of Faults in MTDC System*

Efficient identification, positioning, and separation of defects are essential for ensuring the dependability and stability of multi-terminal HVDC systems. Robust protection techniques are necessary for this, which involve the use of advanced fault detection algorithms, quick fault clearance mechanisms, and coordinated control strategies. Within a multi-terminal high-voltage direct current (HVDC) system, it is possible for faults to arise on both the alternating current (AC) and direct current (DC) components of the system. Multi-terminal high-voltage direct current (HVDC) systems facilitate accurate management of power distribution between several terminals. They achieve this by allowing for dynamic control of power flow and delivering rapid reactions to disruptions in the grid. Therefore, protecting the system against direct current (DC) problems is important. The inability to immediately detect and clear DC faults in the HVDC system might result in temporary instability or complete system failure. Through rapid detection and isolation of malfunctions, the system is able to maintain stability and sustain the supply of power without any disruptions. Let's analyze the various categories of faults that can occur on DC sides:

1) *Pole-to-Pole Faults:* These faults occur when the positive and negative poles of the DC transmission lines come into direct contact with each other, leading to a short circuit. Pole-to-pole faults can result from insulation failures, conductor damage, or switching operations.
2) *Pole-to-Ground Faults:* In these faults, one of the poles of the DC transmission lines comes into contact with ground. Pole-to-ground faults can occur due to insulation failures, environmental factors, or equipment malfunctions.

III. PROPOSED METHODOLOGY

The Adaptive Neuro-Fuzzy Inference System (ANFIS a type of neuro-fuzzy hybrid system) is a powerful computational intelligence technique that combines the advantages of fuzzy logic and neural networks[21]. The ANFIS-based method is used to determine the DC faults in our sample multiterminal VSC-HVDC system. This methodology is taken for its ability to learn through data given from the system and set the rules automatically without any need of an expert, making it a more smart technique for easily detecting fault [22]. The adaptive neural fuzzy inference system (ANFIS) is a fundamental concept in the domain of artificial intelligence (AI). It integrates the expertise of fuzzy logic and neural networks to deliver precise and effective results. ANFIS is applicable in numerous AI applications and derives from the need to develop a system with adaptive capabilities and the capacity to extract information from fuzzy sets. ANFIS simplifies adaptive modeling and enables the approximation of non-linear and complex functions by combining learning skills from both paradigms. It functions as a key idea, providing a thorough method for drawing conclusions and making decisions. ANFIS was developed in the early 1990s by Jyh-Shing R. Jang. ANFIS is a modelling and result prediction tool for complicated scenarios[23][24]. It is applicable in many recent technologies for its advanced features [25]. This approach provides a way for fuzzy modelling techniques to collect data from a dataset and subsequently calculate the parameters of the membership function that will optimize the ability of the corresponding fuzzy inference system to analyze the input/output data. It is referred to as a fuzzy system that acquires its parameters by processing data samples and utilizing a learning algorithm derived from or influenced by neural network theory. This kind of learning operates in a manner similar to neural networks. The neuro-fuzzy is split into two categories in the field of fuzzy modelling research:

1. Interpretability-focused linguistic fuzzy modelling (mostly the Mamdani model).
2. Accuracy-focused precise fuzzy modelling (mostly the Takagi-Sugeno model).

Because the linear rule consequents of the Takagi-Sugeno fuzzy model are compatible with neural network designs, integrating the fuzzy inference system into the neural network framework utilized in ANFIS is a simple process. The neural network parameters and the fuzzy model parameters can be optimized and trained together without any problems because of this integration. For the protection system, accuracy and precision are the most important factors that attract the use of ANFIS for fault detection, which works in the Takagi-Sugeno Fuzzy Inference System. ANFIS technique with DWT-based feature extraction is also used to give protection in electrical machines [26].

A. *Takagi-Sugeno Fuzzy Inference System*

The Sugeno fuzzy inference system was proposed by Takagi, Sugeno, and Kang in 1985. The fuzzy rule format of the Sugeno Fuzzy Model is given by: If x is equal to A and y is equal to B, then z is equal to the crisp function f(x, y), where z represents the consequent and A and B represent fuzzy sets in the antecedents. The function f(x, y) is frequently represented as a polynomial when considering the input variables x and y. A first-order Sugeno fuzzy model is obtained when f(x, y) is a first-order polynomial. The two primary processes in the fuzzy inference process that are similar are the fuzzification of the inputs and the utilization of the fuzzy operator. The primary distinction between the Sugeno method and Mamdani's approach lies in the fact that the output membership functions in the Sugeno method can be either linear or constant. The outcome of fuzzy rules also has an impact on the differentiation. The Mamdani Fuzzy Inference System (FIS) employs fuzzy sets as the outcomes of its rules, whereas the Sugeno FIS utilizes linear functions of the input variable as the outcomes of its rules. Sugeno's technique can function as an integrating supervisor for linear controllers that are required to be employed since each rule is linearly dependent on the input variables of the system. The Sugeno system utilizes adaptive methodologies to construct fuzzy models. Adaptive approaches can be used to customize the membership functions. Consequently, Sugeno controllers possess a greater number of programmable parameters in their rules, and as the quantity of input variables increases, the number of parameters also increases. The Sugeno approach has the following benefits:

1. It is computationally efficient.
2. It is small and functions well with adaptive, linear, and optimization techniques.
3. The finest application for it is in mathematical analysis.
4. The output surface's guaranteed continuity is included.

B. *Proposed Algorithm*

In this paper, we have developed a fault recognition technique using the neuro-fuzzy designer tool depicted in Fig.

3 to detect the pole-to-ground and pole-to-pole faults without using any signal decomposition or feature extraction, which makes the method easy to use in practical applications without the need for a master operator. As we know, due to a fault, our system's normal operating conditions get disturbed. Mostly, system current and voltage are taken as the deciding parameters for the recognition of faults in the system. The sample system is simulated with the fundamental sample time of 7.4074e-06 using the Power Gui block in MATLAB Simulink software. The sampling frequency for data acquisition is 1 kHz. Hence, DC current and voltage are taken from the rectifier station end as the input for the proposed method. Now generate the data set from the extracted signal. There are 6000 data samples taken in the form of a 6001x1 matrix for current as the input to detect pole-to-ground fault and 6000 data samples taken in the form of a 600x1 matrix for voltage as the input to detect pole-to-pole fault. With the help of a neuro-fuzzy designer, we train this data set to achieve the desired output in the form of trip signals '0' and '1', where '0' is recognized as a normal condition and '1' is recognized as a faulty condition. After successfully training the data set value as input and the trip signal as output, the "FIS" file is generated automatically by setting certain rules using the 'IF-THEN' statement and the 'AND/OR' connector for different fault conditions using the membership function for current and voltage signals on the basis of normal and abnormal conditions. The range of current and voltage is decided for the formation of membership functions by applying pole to ground and pole to pole fault at different locations of the whole line length from one converter station to another converter station (one is acting as a rectifier and another is acting as an inverter) in the four-terminal VSC-HVDC system, which is taken as a sample as discussed in Fig. 2.

When the FIS file is applied to a fuzzy controller, the appropriate input fuzzification processes—which convert crisp values into fuzzy sets—take place. It is now sent to a fuzzy inference system (Sugeno FIS), which makes decisions based on rules established during artificial neural network training. Lastly, the defuzzification procedure is carried out to provide an output by transforming the linguistic value into a crisp value. This is the primary procedure that ANFIS operates on. We do not require the expert to create rules or the hit-and-trial approach to determine the membership function range, in contrast to the fuzzy inference system. The ANFIS method uses appropriate input and output data to automatically generate the rules.

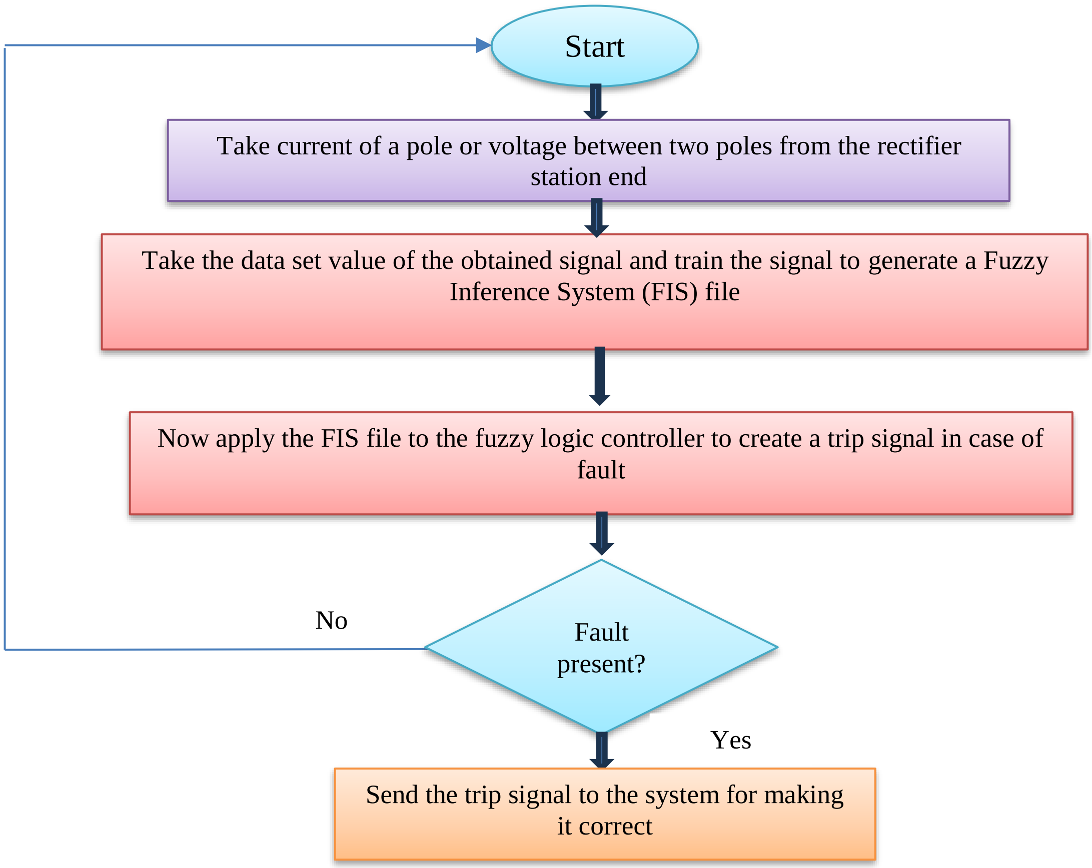


Fig.3. Flow chart of the proposed methodology

Fig. 4 and Fig. 5 represent the normal operating current and voltage in between the DC link, which is 200 km in length in each section of four terminal HVDC systems. So, we can assume that a current value of up to 1000 A and a voltage value of up to 200 KV is safe and considered a healthy operating system.

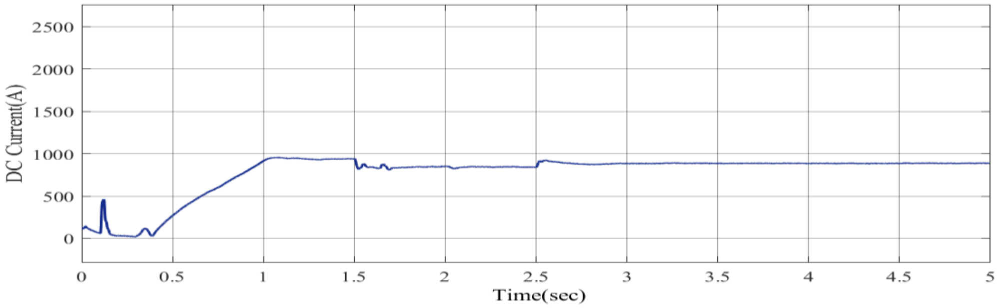


Fig.4. DC current in positive pole without fault.

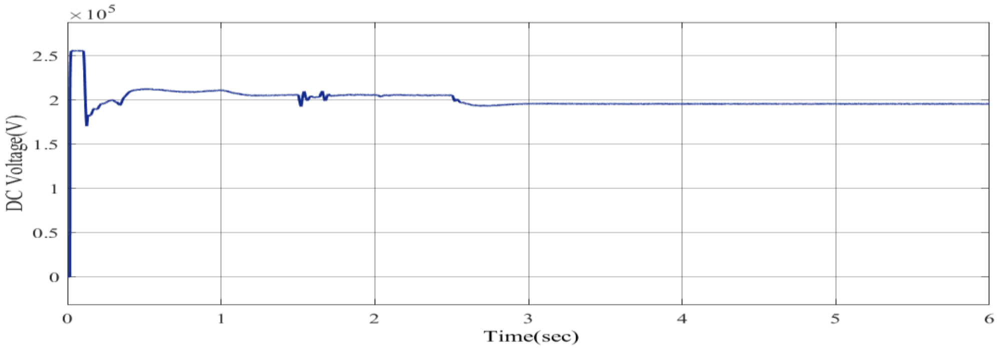


Fig.5. DC Voltage between positive and negative pole without fault.

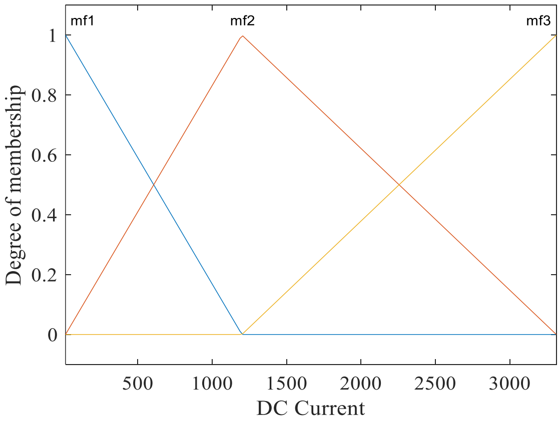


Fig.6(a) Input of ANFIS1 for Pole-to-Ground Fault Detection

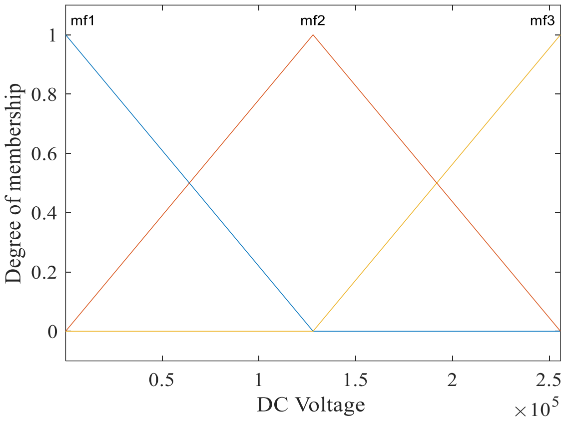


Fig.6(b) Input of ANFIS2 for Pole-to-Pole Fault Detection

Epoch is the process of training a neural network for a single cycle using all of the training data. We use every piece of data exactly once in an approach. A forward pass and a reverse pass combined are counted as one pass. In other words, one epoch ends when your training algorithm has consumed every vector in your training set. As a result, the training technique determines the "real-time duration" of an epoch. Epoch presenting the training vector set (input and/or goal) to a network and recalculating its weights and biases. Keep in mind that training vectors can be given all at once in a batch or individually. Epoch is defined as just an iteration. Every data set is used for training with predetermined weights and biases for every epoch. Each epoch has a maximum size, beyond which weight adjustments occur and repeat for a subsequent maximum size. The training is completed in 1000 epochs with an error tolerance of 0.001, giving the minimal training RMSE of 0.145606 and 0.0693628 for ANFIS1 and ANFIS2, respectively, after reaching the designated epoch.

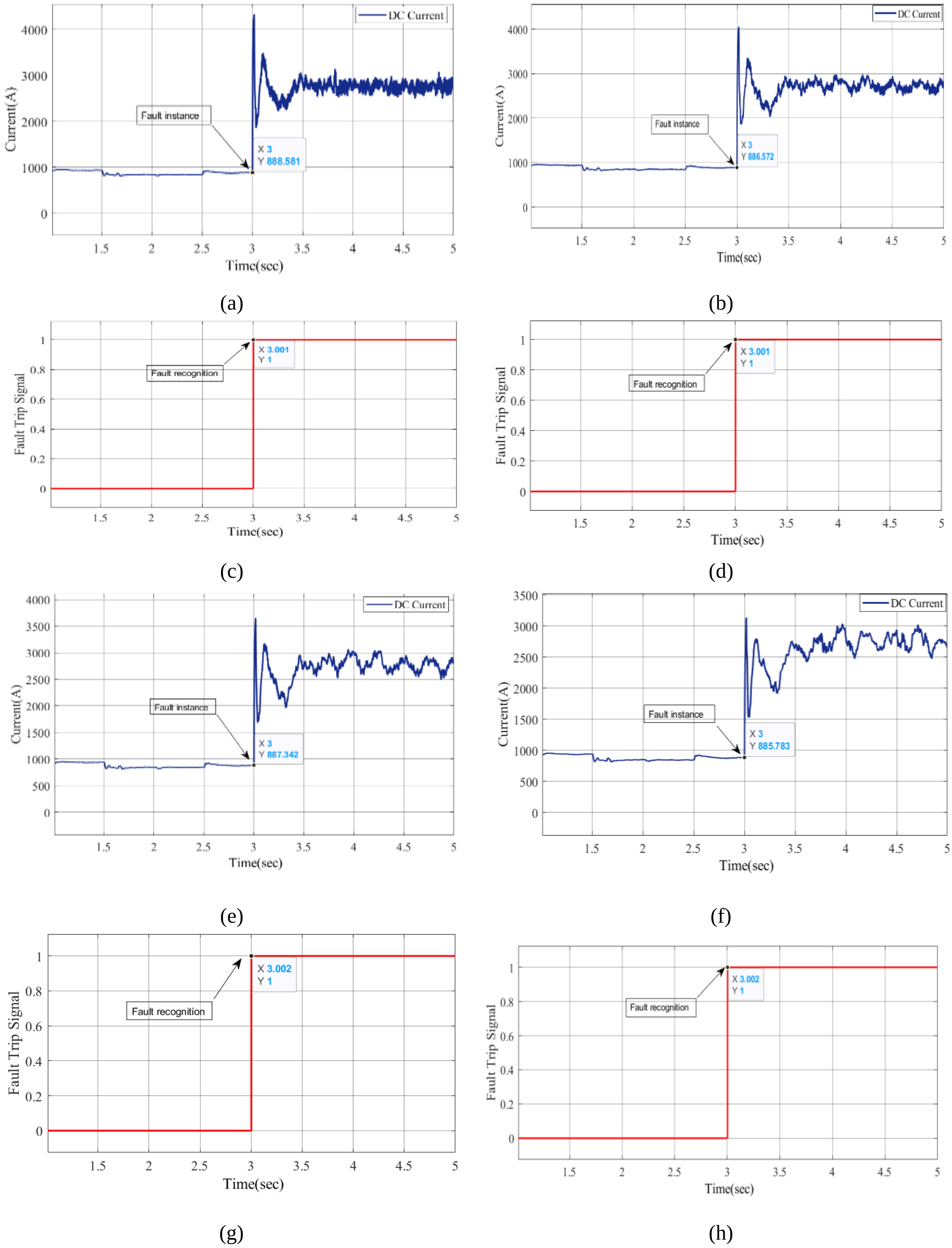
The FIS file name ANFIS1 is generated for the pole-to-ground fault detection with the DC current dataset having membership function represented in Fig. 6(a), and ANFIS2 is generated for the pole-to-pole fault detection with the DC voltage dataset having membership function represented in Fig. 6(b). Three triangular membership functions, mf1, mf2, and mf3, show the range of current and voltage from normal condition to fault condition depicted in Table II.

Table II
Range of Membership Function

	Membership function	**Range**
ANFIS1	mf1	-1632 to 1200
	mf2	15 to 3312
	mf3	1200 to 4961
ANFIS2	mf1	-1.277 e05 to 1.279 e05
	mf2	117.2 to 2.557 e05
	mf3	1.279 e05 to 3.835 e05

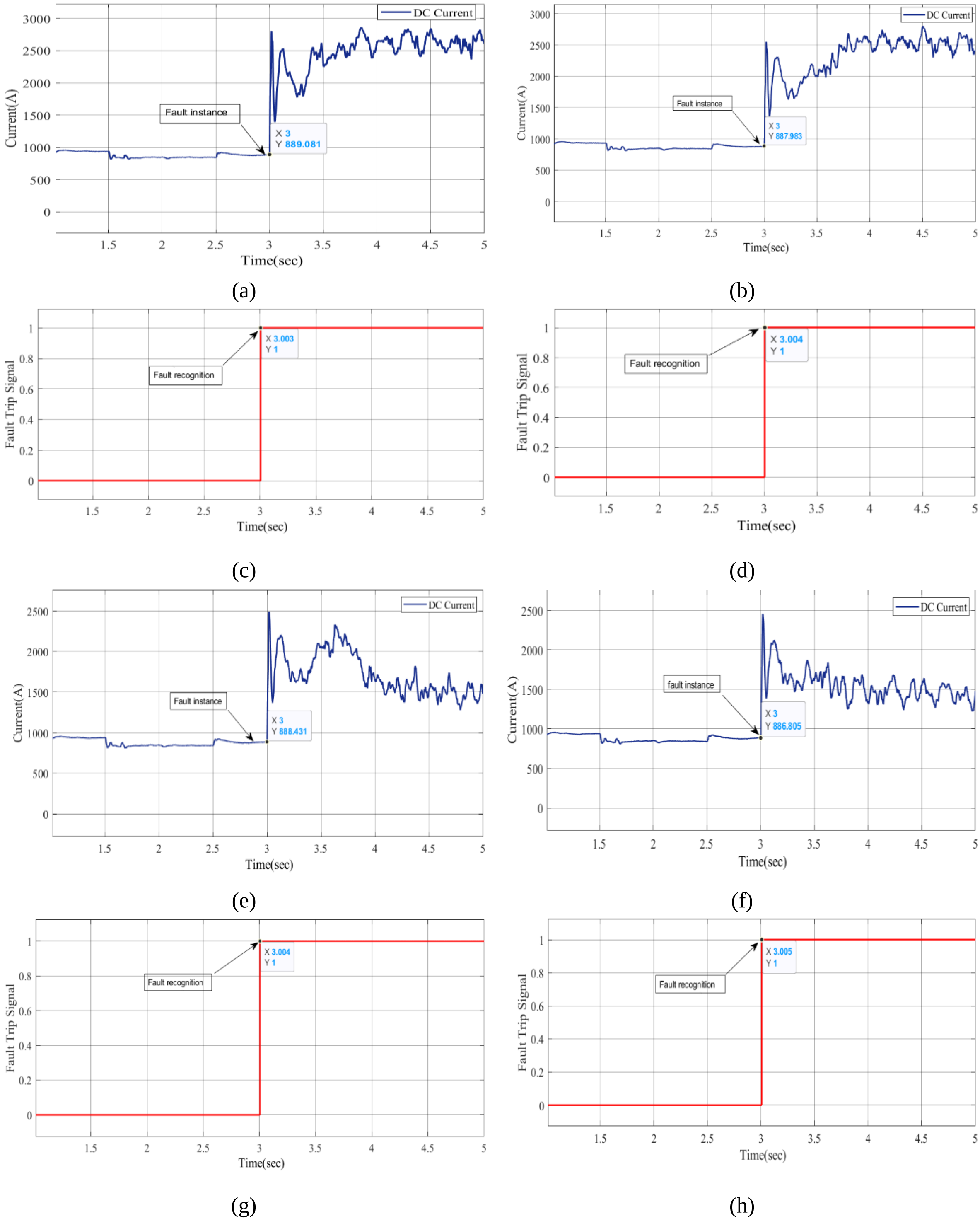
IV. SIMULATION RESULTS

This section illustrates the results of the proposed methodology for four terminal VSC-HVDC systems in MATLAB Simulink. The study of fault is done after 1 sec because 0 to 1 sec is considered the transient period of the system, and after 1 sec, the system achieves a steady state where fault analysis is more convenient. Firstly, a pole-to-ground fault is applied using a DC breaker at different locations in the 200km DC line. The fault is recognized within a few milliseconds after the fault is applied. The results of the detection scheme for different fault case studies are exemplified in Fig. 7 and Fig. 8, along with the current signal when the fault is applied for 3 sec at the line lengths of 5 km, 10 km, 20 km, 50 km, 100 km, 150 km, 170 km, and 190 km. Fig. 7. and 8. show the result in the form of a trip signal '0' during normal conditions and '1' for fault conditions.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig.7. (a), (b), (e) and (f) Pole-to-ground fault current signal at fault instance 5 km, 10 km, 20 km and 50 km and (c), (d), (g) and (h) fault recognition by trip signal respectively.



(a) (b)

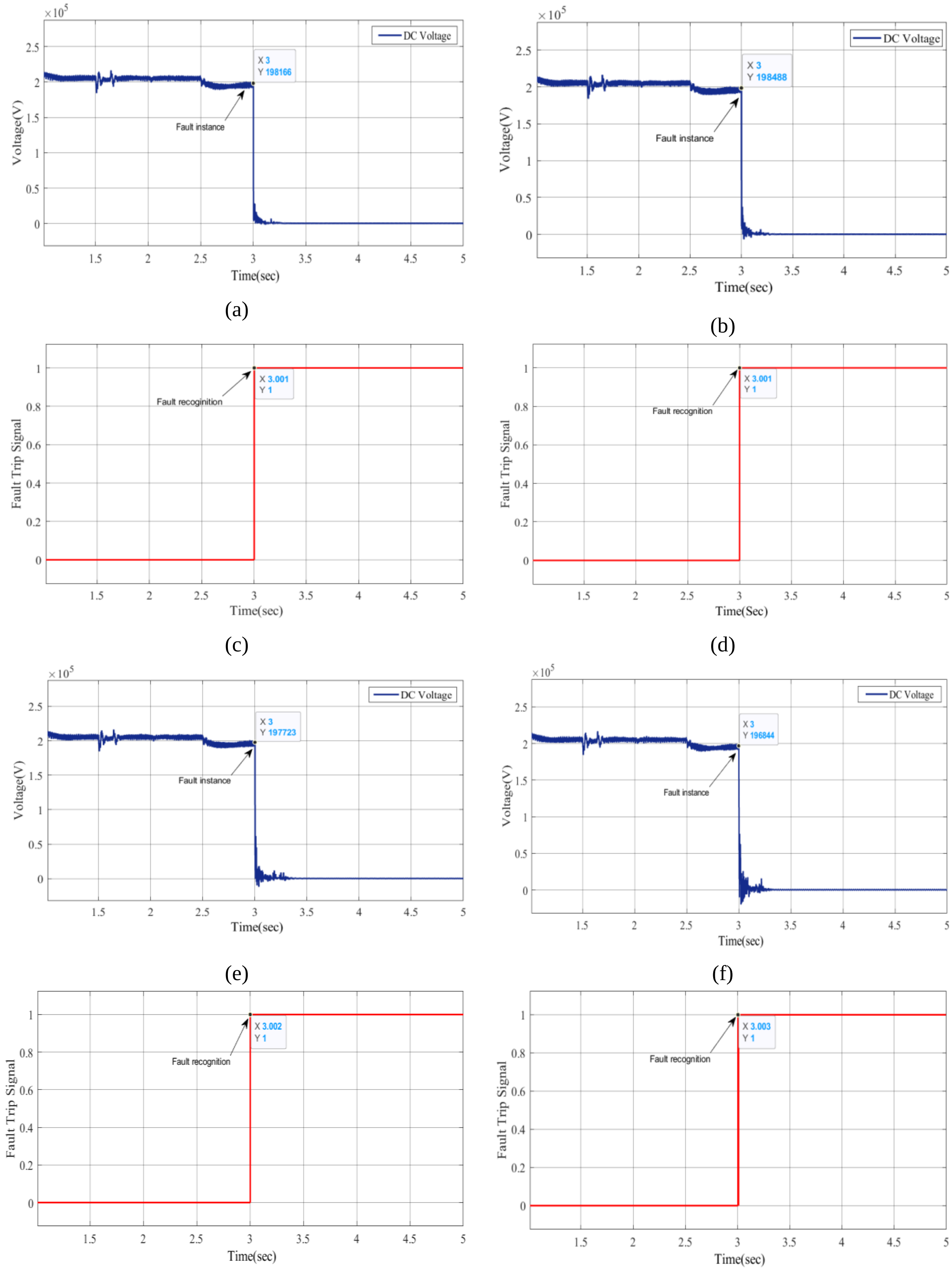
(c) (d)

(e) (f)

(g) (h)

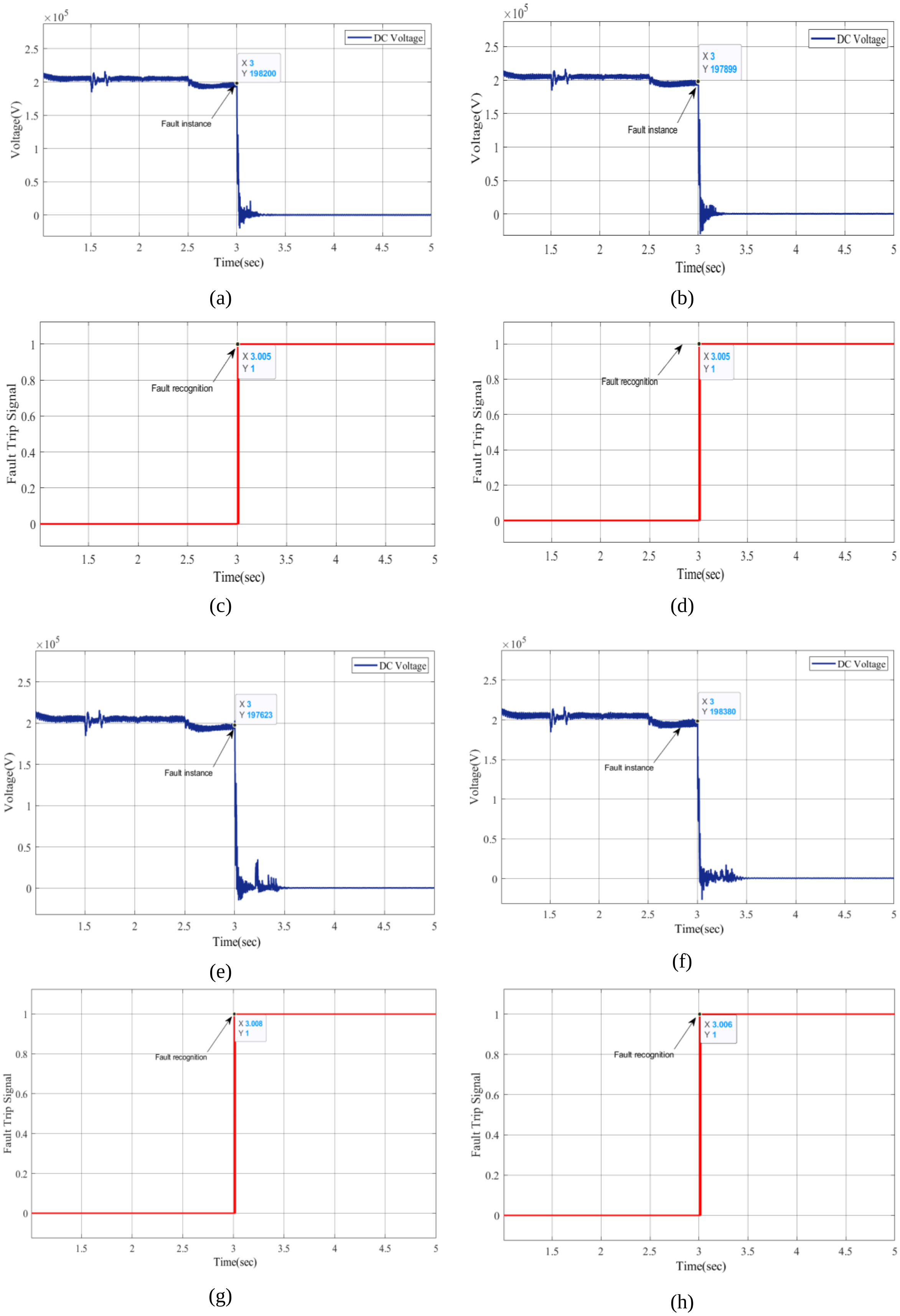
Fig.8. (a), (b), (e) and (f) Pole-to-ground fault current signal at fault instance 100 km, 150 km, 170 km and 190 km and (c), (d), (g) and (h) fault recognition by trip signal respectively.

By introducing a defect into the sample system, the pole-to-pole fault analysis may now be carried out. At line lengths of 5, 10, 20, 30, 50, 100, 150, 170, and 190 km, the DC voltage signal is shown when the fault is introduced at a time of three seconds. The current signal has a very high peak just after the fault is applied, and then it abruptly declines after a few seconds, making fault research on it impractical for pole-to-pole fault analysis. This type of behavior makes fault identification difficult and unexpected. Throughout the 200 km line, the pole-to-pole fault was applied using the DC breaker at various points in time and at various locations. The test results are displayed in Fig. 9, where the DC voltage and trip signal are displayed for various fault sites (5 km, 10 km, 20 km, and 50 km). Moreover, Fig. 10 shows the location findings for the far-end faults at 100 km, 150 km, 170 km, and 190 km. The fault recognition time rises with increasing fault location from the relaying point, yet it stays within the allotted time limit.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig.9. (a), (b), (e) and (f) Pole-to-pole fault voltage signal at fault instance 5 km, 10 km, 20 km and 50 km and (c), (d), (g) and (h) fault recognition by trip signal respectively.



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Fig.10. (a), (b), (e) and (f) Pole-to-pole fault voltage signal at fault instance 100 km, 150 km, 170 km and 190 km and (c), (d), (g) and (h) fault recognition by trip signal respectively.

Discussion

The result of this method shows the effect of pole-to-ground fault on the current signal, which makes the current rise from its normal operating condition, and the effect of the pole-to-pole fault on the voltage signal, which makes the voltage fall from its normal operating condition. This behaviour is the main condition for the bifurcation of normal and abnormal conditions. As we can observe from the result, the fault recognition time is less in the line length near the converter station (rectifier station) from where the current data and voltage data are taken as compared to the line length, which is closer to another converter station (inverter station). Whereas when the distance from the converter station increases, the fault recognition time also increases.

TABLE III
Type of Faults with Fault Recognition Time

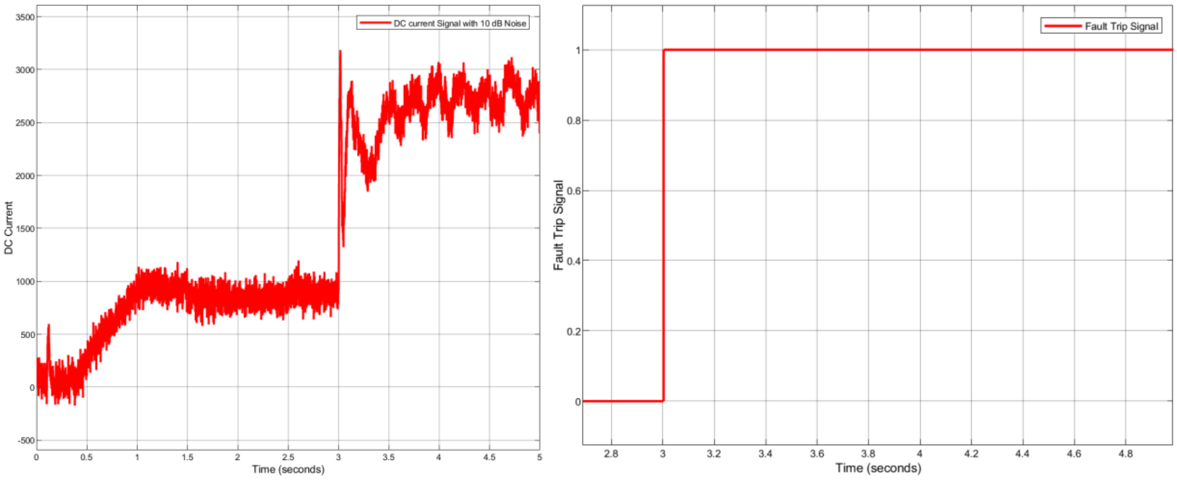
Type of faults	**Fault location**	**Fault instance time**	**Fault recognition time**
Pole-to-ground	**5 km**	**3 sec**	**3.001 sec**
Pole-to-ground	**10 km**	**3 sec**	**3.001 sec**
Pole-to-ground	**20 km**	**3 sec**	**3.002 sec**
Pole-to-ground	**50 km**	**3 sec**	**3.002 sec**
Pole-to-ground	**100 km**	**3 sec**	**3.003sec**
Pole-to-ground	**150 km**	**3 sec**	**3.004 sec**
Pole-to-ground	**170 km**	**3 sec**	**3.004 sec**
Pole-to-ground	**190 km**	**3 sec**	**3.005 sec**
Pole-to-pole	**5 km**	**3 sec**	**3.001 sec**
Pole-to-pole	**10 km**	**3 sec**	**3.001 sec**
Pole-to-pole	**20 km**	**3 sec**	**3.002 sec**
Pole-to-pole	**50 km**	**3 sec**	**3.003 sec**
Pole-to-pole	**100 km**	**3 sec**	**3.005 sec**
Pole-to-pole	**150 km**	**3 sec**	**3.005 sec**
Pole-to-pole	**170 km**	**3 sec**	**3.008 sec**
Pole-to-pole	**190 km**	**3 sec**	**3.006 sec**

V. PERFORMANCE IN CASE OF NOISE

The performance of the proposed method is checked by adding white Gaussian noise of 10 dB, 20 dB, and 30 dB, and the results are reported in Table 4, which confirms that the proposed method is robust against noise. For illustration, a pole-to-ground fault at 50 km is tested wherein the DC current signal is mixed with white Gaussian noise of 10 dB; the results are reported in Fig. 11. It is clear from the test result that the noise does not affect the operation of the proposed method.

TABLE IV
Type of faults with fault recognition time

Type of fault	Fault location	Noise (SNR)	Fault instance time	Fault recognition time
Pole-to-ground	50 km	10dB	3 sec	3.003 sec
Pole-to-ground	10 km	20dB	3 sec	3.003 sec
Pole-to-Pole	20 km	30dB	3 sec	3.002 sec



(a) (b)

Fig. 11 Performance in case of pole-to-ground fault at 50 km with white Gaussian noise of 10 dB
(a) DC Current (b) Fault Trip Signal

VI. COMPARISON

Earlier reported protection schemes are majorly applicable to two terminal HVDC systems, but in this paper, the protection scheme using ANFIS has been developed for multiterminal HVDC systems for the recognition of pole-to-ground and pole-to-pole faults. The main advantage of using the ANFIS-based method is that it provides fast recognition of faults within a few milliseconds under varying fault locations.

VII. CONCLUSION AND FUTURE SCOPE

In this paper, two types of DC fault- pole-to-ground and pole-to-pole fault detection are done using the Adaptive Neuro Fuzzy Inference System (ANFIS). The fault in the entire length of the pole between one converter station and another converter station can be detected using the proposed scheme. The membership function range, which is decided by training the current and voltage dataset, successfully recognizes all possible faults in the pole of the four-terminal VSC-based HVDC system. Because the suggested method just needs pole voltage and current measurements, it doesn't require any communication channel, which makes it both very reliable and inexpensive. The pole-to-ground fault is recognized within 1 millisecond to 5 milliseconds, and the pole-to-pole fault is recognized within 1 millisecond to 8 milliseconds. This method takes very little time to implement and gives accurate fault detection. With the help of this method, the fault can be identified in the system by monitoring the pole current and voltage signal from the control station without using any conventional relay. Once the fault is detected, the system is protected, and the possibility of equipment damage and huge losses decreases. Hence, this method becomes user-friendly and easy to handle. The suggested failure algorithm works well with multiterminal HVDC (MTDC) and two-terminal HVDC (VSC) systems at specific voltage ratings. Systems with varying voltage ratings are not covered by it. If the scheme is created on a per unit basis, it may be applied to any voltage level. Future efforts will take it into consideration. Additionally, we can identify the defective portion in the future by providing an alternative technique that will make it simpler to locate the precise place for manual fault maintenance.

Appendix

TABLE V
MTDC System Parameters

S.No.	Parameters	Values
1.	Resistance (Ω/km)	0.015
2.	Inductance (H/km)	0.792e-3
3.	Capacitance (F/km)	14.4e-9
4.	AC Sources	230 kV, 60 Hz, Short Circuit Capacity 2000MVA

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