A Review Of Various Protection Schemes Of Power Transformers

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Abstract:: The power transformer is an electrical equipment that needs continuous monitoring and fast protection since it is very expensive and essential element for power system to perform effectively. Various methods for the protection are available. Most of the methods should be known for the protection of the transformer before practically protecting the same. Here a review is presented for various methods available for the protection of transformer. The most common protection technique used is the percentage differential logic, which provides discrimination between different operating conditions and internal fault. Some condition as, inrush current and CT saturation can cause mis-operation of differential protection. Few methods to solve this problem are also reviewed. Dissolved gas analysis (DGA) of power transformer is an investigative tool to monitor its health and to detect failures by recognizing anomalous patterns of DGA concentrations is also discussed. Some additional methods for transformer protection are also reviewed, as thermography method. Finally, a conclusion on different methods available for better performance is presented.

Key words: Dissolved Gas Analysis (DGA), Differential Protection, Current Transformer (CT) saturation, Magnetizing Inrush Current.

1 Introduction:

Power transformers are some of the most critical and expensive pieces of equipment in electric power systems. The failure of power transformers inevitably has a serious negative impact on the power supply and may result in massive power blackouts and high maintenance costs. Hence, maintaining the reliability of power transformers is the most important task in an electric power system. Suitable methods for power transformer fault detection and protection schemes should be considered and hence ensure stable and reliable energy delivery [22].

The most common protection technique as shown in Fig. 1, is the percentage differential logic, which provides discrimination between an internal fault and an external fault or a normal operating condition. However, a simple detection of a differential current is not sufficient to distinguish internal faults from other situations that also produce such a current. Some of these situations appear during transformer energization (inrush currents), current transformer (CT) saturation, among others, which can result in an incorrect trip. The correct and fast discrimination of internal faults from the other situations mentioned is one of the challenges for modern protection of power transformers. New algorithms that have been developed for differentiating between internal fault current and other situations that also produce such current should be known for proper maintenance of power transformer as it is an essential element for power system [9].
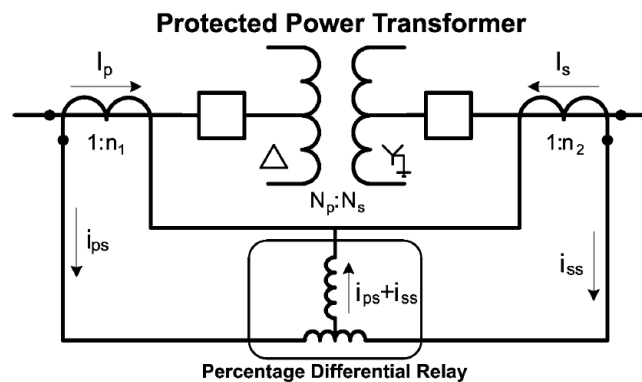

Figure 1. Differential relay connection diagram.

Among the available transformers, oil-immersed power transformers play important roles in voltage and current conversion in modern electric power systems. An oil-immersed power transformer contains a large amount of insulating oil. The goal of the insulating oil is to reduce the temperature and increase the efficiency of energy production. The purpose of the insulating oil is to isolate the insulating material from the body, suppress corona or

arc, and serve as a coolant. In addition to the cooling it provides through the process of the cooling power system, the insulating oil also provides some electrical insulation between the internal live parts to maintain long-term stability under the high temperature. Moreover, it is necessary to regularly sample and analyze the oil quality to determine whether the oil has latent defects for effective treatment.

The insulating oil in power transformers will dissolve nine kinds of gases if the content of any combustible gas is greater than the standard value (ANSI/IEEE C57.104). For safe operation, the power transformer must be shut down for maintenance or repair. The detection results show that the gas content of hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), and carbon monoxide (CO) exceeds the standard value and needs to be included in tracking or performing inspections and maintenance to identify the cause of failure [22]. The amount of any gas produced in a transformer is expected to be influenced by age, loading, and thermal history, the presence of one or more faults, the duration of any faults, and external factors such as voltage surges. The complex relationship between these is, in large part, the reason why there are no universally acceptable means for interpreting DGA results.

A. Fundamental of DGA

The Dissolved Gas Analysis (DGA) has been used for more than 30 years [1] - [4] for the condition assessment of functioning electrical transformers. DGA measures the concentrations of hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon-monoxide (CO), and carbon dioxide (CO_2) dissolved in transformer oil. CO and CO_2 are generally associated with the decomposition of cellulosic insulation; usually, small amounts of H_2 and CH_4 would be expected as well. C_2H_6, C_2H_4, C_2H_2, and larger amounts of H_2 and CH_4 are generally associated with the decomposition of oil. the acceptable level of various gases with respect to the age of equipment are mentioned in Table 1, [2].

Table 1. Acceptable Levels Vs Equipment Age, in ppm

Years	C_2H_2	C_2H_4	H_2
<2	20	10	200
2-5	40	40	5000
5-10	40	100	500
10-20	10	40	200
>20	10	-	40

. All transformers generate some gas during normal operation, but it has become generally accepted that gas generation, above and beyond that observed in normally operating transformers, is due to faults that lead to local overheating or to points of excessive electrical stress that result in discharges or arcing. Dangerous levels of various gases for different types of faults are mentioned in Table 2, [2].

Table 2. Dangerous Levels Vs Type of Fault (Power Transformer PT), in ppm

Fault	C_2H_2	C_2H_4	H_2
Undiagnosed	200	500	200
Hot Spot	600	600	400
Arcing	100	100	100

The commonly used protection for transformer is the percentage differential protection [5], but sometimes this protection may not be able to differentiate between internal faults and other situations that produce similar current. The situation which can produce similar current can be sympathetic inrush current, transformer energization, current transformer saturation which leads to its misoperation, etc., can be the cause for incorrect tripping. Concerning the identification of internal faults as opposed to inrush currents, the approach traditionally used is the aforementioned differential logic together with harmonic restraint. In this method, transformer inrush current due to energization is recognized on the basis of second and other harmonic components obtained by filters.

2 Different Transformer Protection Techniques

A review of different methods available for protection of transformer are presented here. The basic method used for transformer protection is percentage differential protection and for assessment purpose Dissolved Gas Analysis (DGA) is being used for few decades.

Various methods to improve the differential protection [5]- [12], [42]- [46], of transformer have been developed. Few have proposed the same [6]- [8], by the use of wavelet transform, others by different transform [11], [12]. Rest have use restraint method, fuzzy system and hybrid systems [5], [9], [10]. To distinguish between magnetizing inrush current and internal faults in transformer some methods [34]- [36] were discussed separately which is a required for correct operation of differential protection.

Since the use of differential protection of power transformer, current transformer has been used for current measurement purpose. For differential transformer protection, current transformer (CT) saturation has been one of the

main problems. This problem leads to inaccurate measurement of primary currents that may cause relay mal-function. Saturation also increases current measurement error that creates a false differential current. It is impossible to predict or even estimate this error due to the unpredictable nature of CT saturation (many factors such as fault level, fault inception angle, system configuration, CT remanence etc. affect level of saturation and measurement error) [21]. This false spill current may cause spurious relay operation under through-faults. Various methods of detection as well as correction have been developed [7], [13]- [20], [39], [40]. Few methods are hardware solution [14], [17], detection as well as compensation methods [13], [15]- [17], [20] are also developed and prevention methods are also available [14], [19]. By the use of Savitzky-Golay Filter current transformer saturation detection method is also presented [18]. Dissolved Gas Analysis (DGA) has been used for a long time, but it has limitation as the amount of any gas that is produced in a transformer is expected to be influenced by different factors like, age, loading, and thermal history, the presence of one or more faults, the duration of any faults, and external factors such as voltage surges. The complex relationship between these is, in large part, the reason why there are no universally acceptable means for interpreting DGA results. Even though having limitation DGA has been used and different methods [22]- [30] to improve it has been developed. Few have tried to improve the accuracy [23], genetic algorithm [25], fuzzy logic [28] and Artificial Intelligent [29] have also been used for DGA.

Few new methods are also proposed [31]- [33] other than discussed above. In one method frequency response analysis (FRA) [31] was used for transformer protection, in the next method [32] thermography along with AI was used and [33] time-frequency analysis of differential current is presented for protection of transformer.

A. Various Differential Protection

As discussed, the basic method to prevents the transformer is differential protection. Various methods are developed to improve the performance of the same. Few methods are reviewed here.

Three methods which is based on wavelet-based transformer differential protection were proposed.
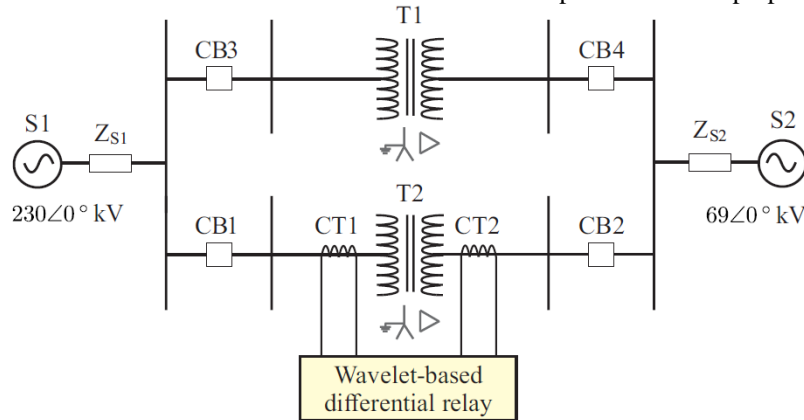

Figure 2. Single line diagram of the electrical system for detecting internal faults during inrush conditions.

a. It has been proposed about differential protection for detecting internal faults during inrush conditions using boundary discrete wavelet transform in order to improve safety as well as reliability of the differential protection relay during transformer energization [6]. The single line diagram used for the method is shown in Figure 2.

b. Fast and efficient transformer differential protection scheme with additional differential CT saturation and cross-country fault detection modules after the external fault detection was proposed. All this was based on the differential wavelet coefficient energy with border distortions in order to stabilize the relay during external faults and distinguish accurately CT saturation from cross-country internal faults [7]. The single line diagram of the system developed is shown in Figure 3, below.
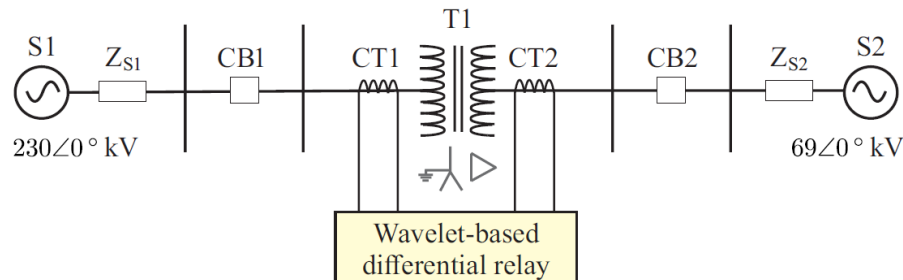
Figure 3. Single line diagram of the electrical system for fast and efficient
transformer differential protection scheme.

c. Related to wavelet-based transformer differential protection, it has been analyzed that internal faults and other disturbances can be properly detected using wavelet transform. But after recreating the phase current and the negative-sequence current differential elements by means of boundary wavelet coefficient energy, shows fast, accurate, was not affected by inrush currents in transformer energizations and fault clearance very effectively [8]. The single line diagram shown below Figure 4, is developed for the stated method.
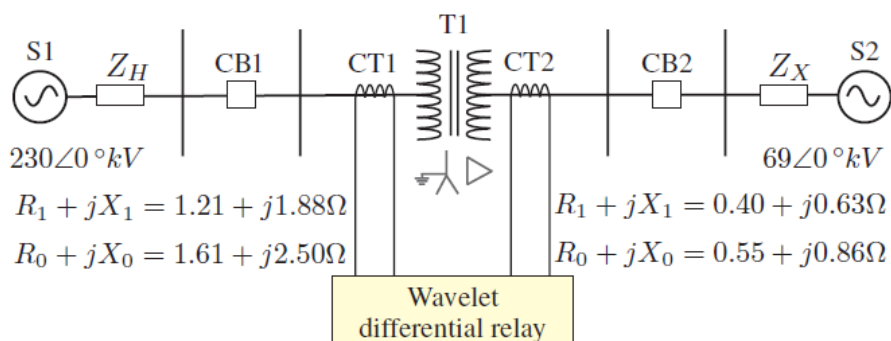

Figure 4. Single line diagram of the electrical system for internal faults and
other disturbances can be properly detected.

The principle of harmonic restraint and voltage restraint current differential protection are reviewed. The conclusion here was flux-restraint current differential protection technique required fewer computations as compared to harmonic and voltage restraint differential protection [5].

A new algorithm was developed to improve the differential protection performance. For the required purpose fuzzy logic and Clarke's transform was used. The main idea of using Clarke's Transform is carried out in a pattern-recognition process to discriminate certain conditions of transformers, such as internal faults, overexcitation, sympathetic inrush, and energization. The algorithm has many advantages such as operating time is shorter than that of commercial relay, greater stability for all faults and operating conditions and finally its simplicity [9].

The next scheme proposes the development of a new algorithm to improve the protection performance by using fuzzy logic, artificial neural networks and genetic algorithms. An ANN was used to reconstruct saturated current signals, as it is mostly used for pattern recognition and a GA was used to estimate the fundamental component and harmonics. A set of inference rules and subroutines based on fuzzy logic were developed in C++ language in order to discriminate internal faults from other operating situations [10].

Combining the features of biased restraint characteristic (BRC) of the conventional differential relay and out-turn of chirplet transform (ChT) in a two-stage algorithm is developed. This algorithm possesses the advantages of both BRCs in the first stage and ChT technique in the second stage. The BRC improves the speed of operation in the high-set zone and non-trip zone, whereas the second stage of the proposed differential protection algorithm (DPA) ensures the discrimination accuracy based on time-varying frequency characteristics [11].

Differential protection of power transformers has been suggested using the application of time-time (TT) transform. At first, external and internal disturbances are discriminated. If the disturbance is external, relay scheme restrains more analysis and tripping. Otherwise, the differential current signal is analyzed by TT-transform and TT-matrix is computed. Next, a suggested index is computed, accordingly. Discrimination between inrush current and internal fault is performed by the proposed index [12].

Two new methods were proposed, current change ratio (CCR) and percentage area difference (PAD) to solve a problem of how to distinguish between internal faults and inrush condition when transformer is switched on which causes the mal-operation problem in differential protection scheme [34]. A method was proposed which is efficient method for discriminating magnetizing inrush and internal fault currents in three-phase transformers based on the auto-correlation function [35]. Using a different geometrical structure of inrush current with respect to that of fault current for the identification of transformer magnetizing inrush for transformer differential protection [36].

To discriminate inrush, internal, and external fault in power transformer using phasor angle comparison and biased differential principle was presented. The new scheme for the transformer protection based on an average angle of second order derivative of differential current for inrush detection and further discrimination of fault is carried out based on percentage biased differential combined with phase angle comparison between primary and secondary current [37].

B. CT saturation compensation methods

Current transformer is used in differential protection for current measurement. If the measurement is not accurate the differential protection may mis-operate. Two main causes of CT saturation include [38]:

i. CT saturation due to the exponentially decaying DC component of fault current and
ii. CT saturation due to the large DC component of inrush current, which leads to incorrect measurement of current. Current measured should be correct for differential transformer to work properly.

Various methods are reviewed for avoiding, detecting, correction/ compensation of CT saturation.

It has been shown that the use of an adjustable switched resistor demagnetization method instead of fixed switched resistor demagnetization method will prevent saturation in protective CT core. Also, a control procedure was proposed for this method [14]. This is a hardware solution. The next hardware solution proposed method uses a negative voltage feedback and applies it to CT secondary side. The injected voltage opposes the excitation voltage of CT in a manner that the magnetic flux of CT remains almost constant under saturation level for any faults. This method is also a hardware solution and is low cost method [17].

For fast and accurate detection and compensation of CT saturation using Kalman Filter (KF) theory was developed. This proposed method has an advantage as it requires a single sample point to detect the CT saturation and it can also cope up with the problems of measurement noises and harmonics [13].

For detection and compensation of CT saturation effects, based on: a least error squares (LES) filter which estimates the phasor parameters of the CT secondary current; a novel saturation detection method which uses the output of the LES filter for saturation detection; and a new minimum estimation error tracking approach which enhances the precision of the phasor estimation. The proposed algorithm [15], was able to reconstructs the distorted current waveform, under dc and ac saturation conditions, with the required precision and speed and also able to performs satisfactorily under inductive burden and under deep and slight saturation conditions.

An efficient compensation algorithm to reconstruct both of the fault and inrush currents which are distorted by CT saturation is proposed. Deformed Signal Compensation (DSC) and DC Offset Current Compensation (DOCC) is used in this algorithm. The proposed method [16], has advantages like its accuracy, fast response time, desired sample-by-sample output, no dependency on power system topology, immunity against noise and harmonics, and its simplicity.

C. Dissolved Gas Analysis (DGA) for Transformer Operation Assessment

The early detection of power transformer failures will ensure the safe operation of transformers. So it is beneficial to develop the early-fault-forecasting technology for transformers. Dissolved gas analysis (DGA) is a technique that is used to detect or diagnose the transformer faults based on the dissolved gases due to the electrical and thermal stresses influencing the insulating oil.

A novel approach is proposed to enhance the diagnostic accuracy of the transformer faults based on introducing new gas concentration percentages limits and gases ratios that help to separate the conflict between the diverse transformer faults [23]. For this teaching-learning based optimization (TLBO) has been used to improve the diagnostic accuracy of transformer faults by adjusting the percentage gases concentration limits and the gases ratios through the proposed two different scenarios. The acceptable level of various gases in different equipment is mentioned in Table 3, [2].

Table 3. Acceptable Levels Vs Equipment Type, in ppm

Type	C_2H_2	C_2H_4	H_2
Power Transformer	20	500	200
Power Transformer- Tap changer communicating with the main tank	200	500	250
Instrument Transformer	40	40	500

A methodology was proposed for diagnosing faults in oil-immersed power transformer using DGA. It is also first work which has considered the optimization of the maintenance cost. The scheme can also be used as an initial stage method to find if the transformer is going to have a fault, and according to the gas analysis it can be determined, which kind of fault is expected or for manual inspection the transformer can be shutdown [22].

As it is known dissolved gas analysis (DGA) in power transformer is an important basis for transformer insulation fault diagnosis, which provides full evidence for general internal transformer hidden dangers. But because of the stochastic growth and the small quantity of time-sequence data, forecasting the accurate dissolved gases content in power transformer oil is a complicated problem. Least square support vector machine (LSSVM) has been successfully employed so it can solve regression problem of nonlinearity and small sample [24]. To further improve fault diagnosis by dissolved gas analysis (DGA) accuracy, a new hybrid feature selection approach combined with a genetic algorithm (GA) and support vector machine (SVM) was presented [25].

Although great efforts to improve the accuracy of transformer fault diagnosis by dissolved gas analysis (DGA), accurate detection of multiple latent faults is still a difficult problem. Therefore, a multifactorial condition assessment method based on fuzzy sets and factor space is proposed [26]. This is a mathematical method for the power transformer

condition assessment. Another method to further improve fault diagnosis accuracy by dissolved gas analysis (DGA) of power transformer, a new fault diagnosis model based on fuzzy C-means (FCM) clustering algorithm and improved principal component analysis (IPCA) is proposed [27]. This proposed method normalizes raw dataset with relatively percentage of gas concentration and regards cluster centers of sample matrix as reference sequence.

The next method, proposes use of dissolved gas analysis results, to detect and isolate the internal faults of power transformers by applying a fuzzy logic method [28]. The method proposes a new classification system of defects and faults based on parts and structures in the power transformers and artificial intelligent algorithms along with dissolved gas analysis data [29]. Similar to previous method, this is for classification of fault and failure types determined by dissolved gas analysis for transformers. In this study, the locations of fault and failure that can be visually identified during internal inspection are determined by classifying the fault and failure types by dissolved gas analysis (DGA) [30].

D. Artificial Intelligence for Protection of Transformer with Thermography and other methods

Dissolved gas analysis of insulating oil in refrigerated power transformer oil is a widespread technique for detecting incipient faults. However, this technique involves safety procedures for the collection of oil samples, laboratory response times and, in some cases, removing the transformer from operation. Removing a transformer from operation in certain situations can become very costly as there are production environments that must run uninterrupted so that stoppages such as this represent financial loss. Infrared thermography, is a non-destructive temperature measurement technique commonly used to detect anomalies and predict possible faults without disrupting system operation [32]. In this method infrared thermographic images were captured on three sides: the front face (Face B) and the lateral faces (Faces A & C) as shown in Figure 5.
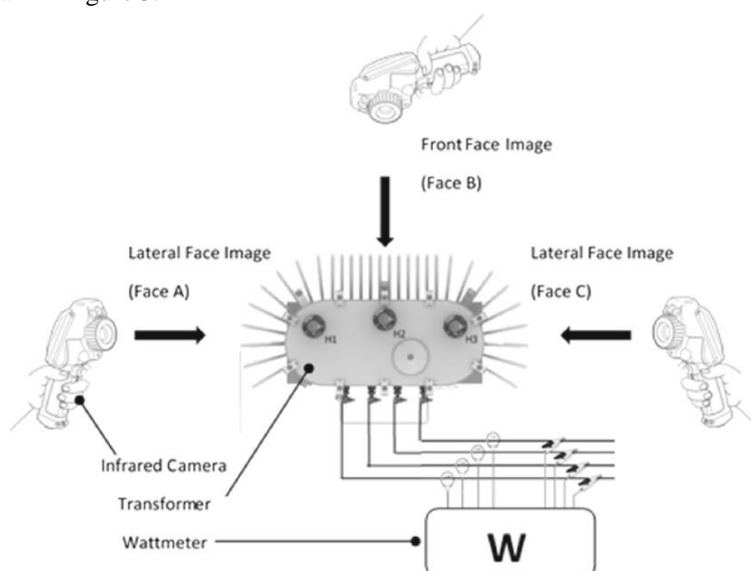

Figure 5. Infrared thermography measuring of the transformer

The artificial neural network(ANN) in this method [32], recognizes the lowest calculated error the correlation between the input data (thermographic images) and the output (result of the insulating oil analysis). ANN could correctly assign 92% of the transformer records diagnosed without fail and 79% of the transformer registers diagnosed with failure. The total percentage of correct classification is 86%. The other approach for thermography is fuzzy logic which could correctly assign 82% of the transformer records diagnosed without failure and 85% of the transformer registers diagnosed with some type of failure. The total percentage of correct classification is 83%.

The two proposed simulations (ANN and FIS) have the same purpose of searching for an intelligent system of thermographic image recognition to correlate with the operating conditions of a power transformer. The results show that both the ANN approach and the fuzzy inference system are well suited to diagnose incipient overheating faults in power transformers of similar voltage classes and constructive aspects. The ANN showed a low 14% error of classification in the test set, while the FIS showed 17%.

Frequency response analysis (FRA) is used as a reliable tool for fault detection in transformers [31]. Number of transformer faults which can be identified by FRA has also increased but, to classify and distinguish the faults is a difficult step. Intelligent classifiers (probabilistic neural network, decision tree, support vector machine and k-nearest neighbors) are used to classify transformer faults. The validation of the method was done by comparing the data obtained from real transformers and the performance of the classifiers which was designed.

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The most important faults that occur in the transformer and can be identified by the FRA method [31] are:
- Axial displacement (AD)
- Radial deformation (RD)
- Disc space variation (DSV)
- Short circuit (SC)
- Deformation of core sheets (DCS)

The detection and classification of a fault and abnormal conditions that occur in power transformers based on improved S-transform. The new method, for fault detection in power transformers has been proposed. HST (hyperbolic S-transform) has been used as time-frequency analyzer of non-stationary differential current signals. The combination of some extracted harmonic components as well as new extracted features based on HST leads to the definition of a new index for a power transformer protection scheme [33].

3. Conclusion

Power transformer is an important component of the power system. The protection of power transformer is utmost important, mainly done by differential protection. But few situations are present which can cause the differential protection to fail, such as magnetizing inrush current and CT saturation. Few methodologies have been reviewed here to differentiate between inrush current and internal fault. Along with inrush current, different methods for CT saturation detection, correction, detection as well as compensation have been reviewed. A couple of hardware solution are also reviewed to avoid the CT saturation. Few methods for protection of transformer were presented, those were different from differential protection.

Differential protection works when the fault has occurred, but it's even better to know the fault before it occurs. This can be done with the help of Dissolved Gas Analysis (DGA). Different methods using DGA have been review, also some methods to improve the accuracy have been discussed. FRA can also be used to identify various faults in the transformer as axial displacement, radial deformation, disc space variation, short-circuits, and core deformation. Artificial Intelligence provides a great reliability for the transformer protection as the percentage error in AI is very low.

This review will help engineers, working for transformer protection to know various methods are available for transformer protection i.e. to detect the fault accurately or to avoid the fault beforehand. It can be concluded that there are no boundaries to develop transformer protection and the same can be an interesting subject for future work.

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