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Power transformers monitoring based on electrical measurements: state of the art

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Abstract: Faults diagnosis in power transformers has been traditionally based on the insulation resistance measurement, polarisation index, analysis of dissolved gasses in oil, dissipation/power factor measurement, and partial discharges within many other alternatives. Originally, all these techniques presented an offline implementation, that is, with the transformer out of service. Currently, some of them, such as partial discharges measurement or gas analysis (gas chromatography), are carried out online in those cases in which the importance of a machine justifies it. These techniques have been recently complemented with new alternatives, such as frequency response analysis, an offline application technique. At the same time, in recent years, development of online diagnostic strategies has been carried out only based in monitoring of electrical variables. These techniques have the advantage of being economical in relation to traditional ones. Its development are incipient and with high growth potential. This study presents a review of the most important techniques and a critical comparison between them.

1 Introduction

Power transformers are among the most important components in a power system. Avoiding damage to power transformers is vital; otherwise, continuity in power delivery may be seriously disrupted. Furthermore, repair or replacement is expensive and time-consuming [1].

Failures in power transformers can be originated by external causes (humidity, chemical dust, electromagnetic radiation, or environmental phenomena among others) or by internal causes (overheating, mechanical displacements of the core or windings etc.) [2]. The most frequently faults in power transformers consist of insulation problems, particularly in windings and bushings [3]. For this reason, an adequate maintenance should be fundamentally oriented to the monitoring of the parameters that characterise the state of these elements [4].

Approximately 40% of the faults are originated in the active part (windings and core) in transformers without on-load tap changer (OLTC). In transformers with OLTC, the percentage is lower because the changer becomes in the most susceptible element of failure [5]. Furthermore, around 75% of the faults in the active part are inter-turn short-circuits (ITSC) [6]. ITSC can be categorised as: turn-to-turn in one-phase, phase–phase, and phase–core [7].

The faults occurred in the windings can be divided into long-length faults and short-length faults according to the number of turns involved. The first group usually results in high terminal currents and therefore, could be detected effectively by protective relays [8]. The second group corresponds to insulation faults between a few turns of the winding. These faults could be originated due to low quality of insulator or damaged insulation during manufacture process. This kind of faults generally produces small variations in the terminal currents of the transformer, difficult to be detected by means of the conventional protection relays. However, in these cases, it could appear fault currents with considerable amplitudes in the faulty circuit. If these faults are not detected quickly, they could produce irreversible damage [9].

It should be noted that when an ITSC occurs, the current in the fault loop not only depends on the fault resistance but also on the position occupied by the failed turns inside the winding [10]. This particularity makes difficult to determine the severity of a failure to reach an accurate diagnosis.

When a large number of turns are short-circuited, the fault produces high currents that are mainly limited by the dispersion reactance. However, when very few turns are affected, the influence of the winding resistance can become dominant, reducing the terminal currents to a small fraction of the rated current. In [11], the effects of fault resistance for different numbers of turns in short circuit and for the case in which there are conductors in parallel are analysed. It is concluded that if there is a short circuit of very few turns, particularly a single turn between parallel conductors and the fault is near the centre of the coil, the differential currents could be small to a such extent that conventional differential relay may not detect them. In these cases, new protection techniques based on negative sequence currents or frequency spectrum analysis of the primary current are being used.

Moreover, short-circuit currents caused by external faults in the transformer impact in the windings and in their magnetic core with great mechanical stresses. This could cause deformations in the core columns or in the windings that brings out an inadequate functioning of the transformer [12]. Other causes that can originate deformations are explosions, earthquakes, or deficient transport conditions. The winding deformation may occur from axial or radial movements, buckling, tilt or displacement between high- and low-voltage windings etc. This also could produce other faults such as open turns, short-circuited turns, or partial collapse of the winding. Mechanical stresses could also affect the clamping structures, ground connections of the core or shield [13]. In some cases, slight displacements of turns do not cause immediate failures, but they lead to a progressive deterioration that manifests in the long term.

1.1 General review of traditional monitoring techniques

The aim of early fault detection is to obtain enough time to take a corrective action such as reconfiguration, planned maintenance, or immediate repair in order to avoid more serious damage.

There is a distinction in fault detection methods between online and offline. The online tests are carried out with the transformer in service and allow a real-time monitoring of certain physical quantities that could lead to an ‘instantaneous’ diagnosis of the transformer. In another way, offline tests are carried out with the transformer out of service, either due to a programmed stop or in the case of any eventuality. These kinds of tests have been historically the most common.

Another way to classify diagnostic techniques for power transformers is to separate the most traditional ones from the most innovative or modern. The first ones are those that have been applied systematically for some years, whose virtues have been extensively tested and there are precise standard for their implementation and diagnostic procedure. The last ones are given by new methods that are still in development or in experimental stage. In general, these approaches have an online implementation, an easy interpretation of the results, and a low cost.

Among the traditional techniques, partial discharges measurement (PD) [14], dissolved gases in oil analysis (DGA) [15, 16], frequency response analysis (FRA) [17], infrared thermography [18], dissipation/power factor measurement (Tan Delta) and capacity [18, 19], vibrations and acoustic analysis [20], transformation ratio, polarity and phase measurements [18, 19], polarisation index measurement (PI), core insulation resistance, return voltage measurement (RVM) [18], impulse test [18], dielectric frequency response (DRA) [21], and leakage impedance or short-circuit impedance (SCI) [18, 19] are highlighted. It should be noted that some of these techniques (such as DGA and PD) that were traditionally offline implemented currently offer the possibility of online implementation. However, this possibility usually offers results that are not as reliable as those for offline implementation and are generally expensive and restricted to high-power transformers.

Table 1 shows a summary of traditional techniques differentiating between online and offline, presenting the degree of reliability of the diagnosis and showing its main characteristics.

In the dry insulation transformers, due to their characteristics, the diagnostic technique based on DGA cannot be applied. These transformers are widely used in transportation applications over their oil-filled counter parts, and they are unavoidable in places where factors like safety and cleanliness are of high importance. Traditional techniques have been widely treated in the literature and in many cases, their implementation is standardised. As a complement to these techniques, new proposals have recently emerged. The trend, as in the case of electric drives or generators, is oriented to the online implementation of diagnostic systems [30, 31]. These papers focus on these recent alternatives that offer continuous and low-cost monitoring. Some of them appear as additions to the classic differential relays, while others are based on the analysis of the harmonics of some of the variables of the transformer or in the monitoring of the inverse sequence impedance, among many other possibilities.

The paper aims to present a synthesis of the diagnostic methods that have been recently developed. Each technique is analysed based on the ability to detect incipient faults, the possibility of application in dry insulation transformers, the quickness to identify a fault, the cost of implementation, and the degree of reliability among other characteristics [32].

2 Recently proposed techniques based on electrical variables measurement

Most of new transformer fault detections and diagnosis techniques arise from the implementation of digital relays. This type of relays, currently used massively, requires the measurement of instantaneous voltages and currents. This allows the use of these variables in order to implement new strategies or algorithms without need to incorporate new sensors in the transformer.

A possibility is to incorporate new routine to the differential protection relay. Differential protection has been used as the primary protection of most power transformers for many years due to its reliability, certainty, and speed of operation [28]. It consists on comparing primary and secondary currents of the transformer to verify the lack of leakage currents inside the machine. A limitation in this type of protection lies in the inability to obtain correct diagnoses under transient operating conditions. During the connection of the transformer to the power grid, or in cases where external faults to the transformer cause the current transformers (CT) saturation, the differential relay could give false alarms [29]. In order to avoid these inconveniences, restriction algorithms are applied to maintain stability during transformer energising and saturation events of the CTs [33]. Some works propose to follow the second harmonic of the primary current to detect the inrush condition. A value of this component below a normal one allows the relay to identify the inrush condition and reject a possible failure. More recent alternatives propose algorithms of cross-blocking and independent harmonic blocking [33], Park components analysis [34], symmetrical components [35–37], and discrete wavelets transform analysis (DWT) [38].

Another limitation of this type of protection is that it is only effective to detect faults when a high percentage of turns is involved or there is a phase-to-ground fault [39]. In cases of faults between a small number of turns or with a high limiting impedances, their diagnostic capacity is affected [40]. According to the IEEE standard C37.91-2000 [41], for incipient faults in power transformers or when the number of turns in short circuit is <10% of the total winding turns, there is no significant change in terminal currents. Therefore, the differential protection relay would be unable to detect the fault [42].

Based on the above, it is possible to conclude that through a conventional differential protection (based on a single predetermined performance curve), it is difficult to achieve a high degree of safety and good sensitivity simultaneously. As response to this limitation, in [43], an adaptive method is presented, which can self-regulate the parameters of percentage differential characteristic on the basis of power transformers operating conditions. In this sense, it provides a high operating sensitivity on internal faults during normal, while retaining higher security on all external faults. The proposed scheme is successfully tested to detect dead short-circuit between turns from 1% of the total. Although this method offers an improvement in relation to the traditional relay, it is not applicable to detect failures in the incipient state, that is, with low fault currents. There are many other alternatives that propose, among other possibilities, to analyse the harmonic content of the primary current of the transformer or to estimate parameters such as leakage inductances. All these variants can be applied, with low cost, in transformers without differential relays. Many of these alternatives, in addition to detect an abnormal situation, offers the possibility to make a diagnosis, that is, determining the severity and location of a fault. The most main proposals found in the literature classified according to the principle on which they are based are described below.

2.1 Diagnostic strategies based on models

To carry out strategies based on models, it is necessary to obtain an approximate model for the fault-free condition. The diagnosis consists on monitoring the transformer variables linked to the model. With some of these variables and the model for the fault-free condition, other variables are calculated. Then, the variables obtained through the model are compared with those obtained by measurement. If the transformer works in a 'fault-free' condition, the values obtained in one way or another must coincide. Otherwise, it is considered that the transformer does not respond to the original model and, therefore, presents a fault.

It is important to determine which variables should be measured and which ones will be used as failure indicators for an efficient strategy. Taking into account that in the power transformers, the voltage and current values in primary and secondary windings are available, these variables are generally used to implement the diagnosis. Different alternatives have been presented. Some of them use the ratio of the increments of the primary and secondary winding flux linkages (RIFL) and other ones employ the variation of the differential current in order to check the values calculated by the model with respect to the measured values. The RIFL is based on the calculation of the transformer flux linkages. Measurements of voltages and currents of the primary and secondary are used for this purpose. It is also required to know the values of resistance and reactance per phase of each winding. With the calculated flux linkages, the transformation ratio is determined. When this ratio exceeds a threshold, the presence of an internal fault is considered

Table 1 Most used techniques in power transformers diagnosis

Method	Implementation	Degree of reliability	Most important features
dissolved gases analysis (DGA)	online	high	Good detection and diagnostic capacity. A similar, but more economical alternative, is the equivalent hydrogen method [15]
	offline	high	Very good detection and diagnostic capacity based on laboratory chromatography [16]
furans chromatography	offline	high	Laboratory analysis. Allows to determine the insulation ageing state [18]
infrared thermography	online	medium	Easy interpretation [18]
dissipation/power factor measurement (tan delta) and capacity of windings and bushings	online	high	There are measurement equipments for on-line approaches, with the additional advantage that these values are at the service voltage [22]
	offline	high	Detects insulation degradation before a failure occurs [18, 19]
polarisation index (PI) of windings	offline	low	Index of the quality of the insulation tested. It has major importance with low IR values [18, 19]
core insulation resistance	offline	high	Detects multiple grounding of the core. It is only applicable in cases where the connection of the core to ground can be unlinked [18, 19]
partial discharges (PD)	online	medium	Lack of confidence and robustness (interferences), although it is possible to make precise and traceable measurements [14]
	offline	high	Greater sensitivity than online measurements. It can be measured directly inside the transformer tank with liquid insulation using ultra high frequency sensors (UHF) [18]
insulation resistance (IR) of windings	online	medium	Incorporated in current monitoring systems. It is not traceable with offline measurements
	offline	medium	It detects defects on the insulation, such as deterioration or contamination and faults between windings or windings to earth in extreme cases. PI or DRA test are recommended as complementary tests [18, 19]
transformation ratio (TTR)	online	high	The accuracy of current and voltage transformers make possible to detect very small changes in the properties of the transformer, being comparable to the tolerance limits established for the off-line tests corresponding to IEC and IEEE [19, 23, 24]
	offline	high	Open circuits and short-circuited turns can be detected by measuring the ratio and phase angle of one winding to another [18, 19]
frequency response analysis (FRA) – sweep (SFRA)/ impulse (IFRA)	online	low	The tests to be carried out are limited. Further detailed analysis on injection and signal collection is lacking [25, 26]
	offline	high	Identifies mechanical or electrical faults in the windings, in the contacts or in the power transformer core. SFRA has become one of the common electrical tests and its acceptance in the electric market has increased accordingly [17]
exciting current	offline	high	Evaluates the insulation between coils of the windings, the magnetic circuit of a transformer and the tap changer. Detects short circuits between turns [18, 19]
RETURN voltage measurement (RVM)	offline	high	Slight knowledge of water content in oil–paper insulation and insulation ageing [18]
winding resistance	offline	high	It detects windings faults or contact problems. It is used to check the operation of the OLTC without opening the tap changer compartment [18, 19, 27]
leakage/short-circuit impedance	offline	medium	Sensitive method to evaluate the possible axial/radial deformation or displacement of the windings [18, 19]
differential protection	online	high (with the use of new proposals)	Primary protection for its reliability, certainty, and operation speed [28]. Disadvantage: false operations caused by the magnetisation current [29]
vibrations and acoustic analysis	online	high	Suitable for mechanical faults in transformers and OLTC [20]
dielectric frequency response (DRA) or dielectric spectroscopy	offline	high	Moisture detection and insulation degradation. Increases the sensitivity of the measurement when different frequencies to the power grid frequency are used (some faults are more dominant at low frequencies and others at high frequency) [21]

[44, 45]. This diagnostic technique is immune to external faults or connection transients; however, it has only been shown to be effective for faults that involve >10% of the winding.

Another alternative, presented in [46], develops a model able to predict the value of the differential current in each phase of a transformer. The algorithm requires a calibration stage in which the differential current values for the fault-free condition are established. If there is a short circuit between turns of a winding, the transformation ratio will be affected and the algorithm will observe a difference between the differential current values calculated by the model and those that were measured. The proposal is successfully implemented in a laboratory prototype. However, the strategy does not consider the effects of CT saturation, inrush current, or OLTC operation.

2.2 Diagnostic strategies based on artificial intelligence

Different artificial intelligence (AI)-based techniques have been used in the detection and diagnosis of rotating electrical machine faults [47]. Recently, some of these techniques have been applied for transformers. These techniques are based on the use of artificial neural networks (ANN), fuzzy logic (FL), support vector machines (SVM) [48, 49], and probabilistic neural networks [50, 51] among other variants [52, 53]. These techniques attempt to improve the sensitivity and adaptability to external disturbances of the differential protection relays. Although in many cases, they have been effective, the disadvantages of these techniques lie in the fact that they require specific training patterns and sets of expert rules for each case. Generalisation of the methodology in order to make a common framework to be applied in any transformer is extremely difficult.

One of these proposals presents an algorithm based on a combination of the wavelet discrete transform with a model obtained with neural networks for the detection and classification of internal faults in three-phase two-winding transformer [54]. Simulation results show that its accuracy to detect faults is >98%; however, no experimental results are presented. The results presented only consider short circuits between turns >10%. In this way, in [55], an improvement to the previous algorithm is proposed, which allows to reduce the training time of the neural network. This alternative is based on the use of a back-propagation network for faults location between turns and offers better response times, simplicity, and accuracy in different fault conditions. In the same line of research, in [56], an algorithm based on ANN is presented for fault identification in the transformer. In this method, the first, second, and fifth harmonic components of the positive sequence differential current are the inputs. Although this technique responds correctly to different transient conditions (inrush current and over excitation), it distinguishes internal faults (faults between turns, earth loops) from external (tap change or CT saturation), among other favourable aspects, the method cannot be generalised to be applied to different power transformers.

In [57], a proposal based on FL is presented. The percentage changes of the magnitudes of the negative sequence currents and their phase shifts are evaluated against a fault. These changes are the input variables to the algorithm based on fuzzy logic, whose output is an indicator of the transformer's condition. The proposal presents good results when it is applied (by computational simulation) on a multi-winding power transformer of 100 MVA, 138/13.8 kV. Different percentages of turns are short-circuited on both the primary and secondary side of the transformer. The algorithm is able to determine whether the fault is incipient, intermediate, or severe. Although the fuzzy rules are based on the knowledge acquired in the behaviour of the system (expert criterion), the proposed technique based on fuzzy logic is simple, robust, and able to detect incipient faults at an early stage.

The common point of all these alternatives is that they require the adaptation of the algorithms for each particular case. Although they have only been tested in a laboratory scale or through computer simulations, they arouse interest because their implementation does not require additional costs. On the contrary, its application only requires the incorporation of new software in the differential protection relay controller.

2.3 Diagnostic strategies based on symmetrical components

Negative sequence currents allow identifying asymmetry situations in any three-phase system. In this way, they could be used to detect faults in a transformer (considering that the faults in transformers are generally asymmetric). Asymmetrical external faults or unbalanced loads also cause negative sequence currents. Therefore, the main problem in a differential protection system, which takes the negative sequence current as a fault indicator, is to discriminate internal faults from external faults.

There are two main approaches for implementing the negative sequence differential protection algorithm with internal/external fault discrimination: the directional methods [35, 58–62] and those of percentage restriction of negative sequence current [39, 63–66].

The first ones propose to identify the origin of the fault according to the phase shift between the negative sequence currents of primary and secondary side. It can be proved that if the negative sequence currents are in phase opposition, the fault has an external origin. On the contrary, if the currents appear in phase, it is an internal fault.

The other option, based on the analysis of the percentage restriction of negative sequence current, is based on the fact that the differential current will increase, during an internal fault, in equal proportion to the restriction current (or blocking). The procedure to obtain the negative sequence currents of differential operation and restriction is similar to the classical algorithm [67]. This is: the differential current is calculated as: $I_{\text{dif}} = \left|\dot{I}_1 + \dot{I}'_2\right|$, while the restriction current is: $I_{\text{res}} = \left|\dot{I}_1\right| + \left|\dot{I}'_2\right|$, considering both incoming currents to the protection relay. Ideally, the differential current is only affected by faults within the protected zone, being independent of external faults. However, to avoid measurement errors that arise with severe external faults (CT saturation), the operation zone of the relay is restricted. The trigger signal is given when the differential current is greater than a certain preset value (threshold).

In normal operation, the ratio of the negative sequence currents between primary and secondary in a transformer is given by the transformation ratio; therefore, the relationship between the two currents of a same phase is linear. The same situation occurs in the case of external faults. In the case of an internal fault, the ratio of negative sequence currents between primary and secondary stops responding to the transformation ratio, not only in magnitude but also in phase. As a result, sinusoidal negative sequence currents on both sides have different amplitudes and phase angles. When a fault occurs between turns, the negative sequence current correlation on both sides of the transformer becomes elliptical. In [68], this characteristic of the negative sequence current is used to diagnose and locate faults between turns. The faulty phase is detected by the negative sequence current. The side of the faulty winding is obtained by the ratio of the two diameters of the ellipse obtained from the correlation of the negative sequence current between the primary and secondary side. The main characteristic of this method of faults detection by means of the use of components of negative sequence is that it does not depend on the load or disturbances such as unbalanced loads, unbalanced supply voltages, and external short circuits. On the other hand, the technique is immune to constructive asymmetries and measurement errors [58, 68, 69].

Another possibility, based on the use of negative sequence currents to detect inter-turn faults, is based on the tracking of the phase angle between the negative sequence current components on both sides of the transformer [61]. Although the studies presented in this proposal are limited (they dealt with a particular configuration and a single condition of the system), the idea is attractive because of its simplicity.

In [36], algorithms for inter-turns fault's detection based on the calculation of the increment in the sequence components are presented. The zero sequence current measurement can be direct (by an additional CT located inside the winding if the connection is in a triangle) or calculated from the phase currents. Direct measurement is suggested only for banks of single-phase transformers. The fault criterion for the different alternatives is a voltage signal proportional to the fault current. According to the algorithm used, it is necessary to know the tap position and the value of the leakage inductance between the delta winding and the core. The techniques presented allow the detection of a small number of turns in short circuit not taking their location into account. The speed of the algorithm is extremely fast, approximately one period.

Another possibility is to incorporate the instantaneous phase voltage signals into the algorithms, in order to calculate the positive sequence admittances. In [70], an example of this strategy is presented. The method is based on the mapping of the admittances, seen from the primary and secondary transformer, in the complex plane. It is shown that the locus obtained for normal condition of the transformer is altered before a fault. According to the simulations presented, the proposed technique is able to discriminate between internal and external faults and can also discriminate inrush current situations.

Moreover, in [35], a relay prototype is presented which bases its operation on the monitoring of the negative sequence current and voltage. The proposal offers low response times and it is more sensitive than traditional differential protection. As a difference of the previous proposals, this technique is able to detect faults in the transformer without load. The technique was tested, with satisfactory results, with a fault that involves 3% of the turns of a winding. A more advanced method than the previous ones is to

Table 2 Generalised comparison between AI [48–53, 72, 73], DWT [74, 75], and proposed algorithm

Parameter	AI approach [48–53, 72, 73]	DWT [74, 75]	Proposed
mode of analysis	online	online	online
operating requirement	pretrained network (ANN, SVM)/rules (fuzzy) and online data	online data and threshold	online data and threshold
historical data and expert knowledge	required	not required	not required
constraint	training samples/rules	basis for selection of the mother wavelet	non-stationary signal
effect of change in system parameter on the performance of the algorithm	variation in pattern and possibility of need for recalibration	no effect	no effect
computational complexity	high	high	low

Table 3 Sensitivity assessment of proposed algorithm in [71] with existing methodologies

Parameter	Existing differential protection [76]	Algorithm in [39]	Algorithm in [34]	Proposed in [71]
stability for no fault, unbalanced load, unbalanced source	stable	stable	stable	stable
inter-turn fault detection for fault current of 1 p.u.	15% turns fault	3% turns fault	4% turns fault	2.5% turns fault
dead short-circuit inter-turn fault detection	3% turns	2% turns	1.5% turns	0.5% turns
OLTC operation	fixed characteristic	fixed characteristic	fixed characteristic	adapts characteristics
number of parameters required for setting	4	2	2	2

Table 4 Comparison between negative sequence component and current vector protection algorithms

	Directional method [35, 58–62]	Restriction of I- [39, 63–66]	EPVA [34]
normal operation	negative sequence currents of the primary and secondary side lower than preset value	work in restriction area	only present a DC value
operation with internal fault	phase between negative sequence components of the primary and secondary side less than or equal to preset value	work in operation area	it will contain one DC value and one AC value at twice the power grid frequency
operation with external fault	phase between negative sequence components of the primary and secondary side greater than to preset value	work in restriction area	work in restriction area
sensitivity to detect incipient short circuits between turns	minor	major	major (14% more sensitive than the negative sequence differential method)
reliable discrimination of internal/external fault	low	high	high

analyse, simultaneously, the differences of positive sequence impedances observed from the primary and secondary sides of the transformer ($\Delta Z+$) and the difference between the negative sequence components of primary and secondary currents ($\Delta I-$). These indicators are extremely sensitive in cases of inter-turn faults and stable during normal operating condition of the transformers. In [71], an experimental validation of this technique is presented on a 10 kVA transformer. For this, a differential protection relay was developed based on the $\Delta I-$ versus $\Delta Z+$. The proposed algorithm is able to detect faults between turns in an incipient stage that involves 2.5% turns of the winding. It also offers an improvement in the detection of a dead short-circuit condition (0.5% turns). In the case of OLTC operation, the proposed algorithm behaves adaptively, that is: it adjust the settings according to the tap position. Simulation and experimental studies confirm the stability of the proposed algorithm during transients. In the case of inrush currents, the second harmonic restriction and cross-blocking are used. For CT saturation, the restriction of the fifth harmonic is used, while for under-voltage and over-excitation, a restriction zone is incorporated on the axis of $\Delta I-$, so as to take into account variations in no-load current for overvoltage up to 10% for each tap position [71]. The authors also present a comparative table between the proposed method and other alternatives based on AI (see Section 2.2) and on the wavelet transform (see Section 2.6). This comparison is presented in Tables 2 and 3.

2.4 Diagnostic strategies based on extended Park's vector approach

Other authors have proposed the use of the current vector as a tool to improve the performance of the traditional differential protection of the transformer [77–79]. The differential components of the Park vector (iD, iQ) are obtained by applying the Park transform [80] to three-phase differential currents (idA, idB, idC). In the mentioned works, this strategy is used as a tool to prevent the incorrect operation of the differential protection relay during the inrush transient. The extended Park's vector approach (EPVA) [34] is based on the analysis of the harmonic content of the differential current Park's vector modulus. The authors propose a failure severity indicator based on the ratio between the amplitude of the oscillation and the average value of the EPVA. The implementation of Park's vector [34] is able to detect inter-turn faults for 4% of short-circuited turns.

In [81], finally, an interesting comparison of three of the most sensitive methods to detect low-level turn-to-turn faults in the windings of three-phase transformers is presented (negative sequence component algorithms; directional and restriction method; EPVA). This comparison is shown in Table 4.

2.5 Diagnostic strategies based on ΔV–I locus diagram

By monitoring the voltages and currents in the windings of a transformer, and taking into account the position of the OLTC, it is possible to obtain a graphical representation that reflects the state

Table 5 Effect of the faults in the area of the graph and in the axis rotation

Type of fault	Area	Rotation
interdisk	significant increase	large
disk space variation	increase	very large
leakage fault	increase	large
forced buckling	increase	slight
axial displacement	decrease	none

Table 6 Relative change of ΔV– I_1 characteristic parameters

Type	Parameter	Short-circuit fault (the relative change to the healthy winding)			
		2 (end), %	5 (end), %	10 (end), %	5 (mid), %
50 Hz waveform	U_{in}/U_{out}	1.01	0.95	2.30	1.53
	Δphase	0.04	0.08	0.02	0.13
ΔV–I_1 graph	long axis (a)	−0.04	−0.02	−0.06	0.02
	short axis (b)	−10.70	−22.87	−8.32	−25.10
	slope (k)	−0.99	−0.93	−2.24	−1.48
	eccentricity (e)	0	0	0	0

Table 7 Impact of faults on area and axis rotation of the ΔV–I locus considering harmonic voltage distortion

Type of fault	Impact of fault on ΔV–I locus
short circuit	increase in area + significant clockwise rotation
axial displacement	slight decrease in area + no rotation
radial displacement	decrease in area + slight rotation
disk space variation	significant increase in area + clockwise rotation

Table 8 Effect of faults on the harmonic content of the current [86]

Phase (side)	Short-circuited turns	Fault current, p.u.	Effect after failure	
			Third harmonic	Fifth harmonic
V (AT)	1 turn (0.38%)	0.35	3.1% reduction	2.5% reduction
V (AT)	2 turns (0.77%)	1	5.62% reduction	17.79% reduction
V (BT)	1 turn (0.38%)	0125	6.66% reduction	7.58% reduction

of the transformer. Through a graph in which the differences between the primary and secondary voltages of each phase are plotted as a function of the current of the primary winding, a slightly inclined elliptical curve is obtained. When internal faults occur, such as inter-turn faults, disk space variation, axial displacement or faults between a winding and earth, the graph is altered, adopting characteristic shapes for each particular fault [82].

Table 5 summarises the effect of the most important faults on the area and the major axis rotation of the ellipse in relation to the locus corresponding to the fault-free condition.

In [83], a variant is proposed to detect deformations in the winding of a transformer based on these graphs. The results show that as the short circuit failures increase, the diagrams do not change linearly, but their changes depend substantially on the position where the fault occurs. It was concluded that the curve parameters carry the information of the faults and that the short axis of the curve is more sensitive to short-circuit faults (changes significantly even if there is only one fault between two turns). Table 6 shows the relative change of the characteristic parameters of the curves of the ΔV–I_1locus for different number of turns in fault and for different fault positions.

In [84, 85], the impact of each fault in graphics ΔV–I is analysed by a three-dimensional finite elements detailed model, in order to identify any incipient mechanical deformation within the power transformers.

In [85], besides analysing the impact of each failure in ΔV–I graphs, we examine the impact of different harmonics in order, magnitude, and phase in these graphs, for different types and levels of failure, detailing the increase in the area and the major axis rotation. Table 7 shows the most relevant.

2.6 Diagnostic strategies based on the harmonic content of the current

By performing a trend analysis of specific harmonic components and primary current magnitude, the presence of faults can be detected. The analysis of current harmonics without load and low load in the transformer to detect the presence of inter-turns faults in an incipient stage is presented in [86, 87]. The proposal is based on the use of the Fourier transform and the wavelets transform. The experience presented shows that the proposed approach can detect the presence of an incipient fault involving <2% of the turns and a fault current up to 1 p.u. The fault is manifested in:

- The percentage reduction in the third and fifth harmonic content (Table 8), and as a result, the reduction in the harmonic content or total harmonic distortion (THD) of the primary current (Table 9).
- Increase in primary current depending on severity of fault.
- Variation in approximate and detailed coefficient level of the wavelet transform.

However, the approach is suitable for voltage harmonics within IEEE-specified limits and rated voltage application. Over-excitation or higher voltage harmonics can severely distort the harmonic content of no-load current, hindering the correct interpretation of the results.

Table 10 compares the benefits of the wavelet transform respect to the Fourier transform, considering that the main difference is that the Fourier transform is suitable for the study of perennial harmonic signals while the wavelet transformation allows to establish whether the frequency content is permanent or not, being useful in the study of transient signals.

Table 9 THD reduction due to inter-turn faults (I_f = 1 p.u.) [87]

Phase (side)	Turns	$I_{U\,THD}$, %	$I_{V\,THD}$, %	$I_{W\,THD}$, %
U, *V*, *W* (HV/LV)	0	2.9	3.4	3.4
V (HV)	4	2.9	3.2	3.3
V (HV)	6	3.0	3.1	3.4

Table 10 Comparison between wavelet and Fourier transform [88]

Item	FFT	WT
computational effort	easy	very complex
event detection	minimum	very good
data compression	good	excellent
real-time computing	yes	yes
harmonic detection (frequency)	very good	very good
noise immunity	limited	bad
current usage	high	low

Finally, in [89], the behaviour of inter-turns faults is analysed by the use of high-frequency components of the discrete wavelet transform in the primary and secondary currents. Simulation results are presented with faults that involve at least 10% of turns. The work shows that depending on the connection of the windings, a fault can be manifested in the phase or zero sequence components. The technique is original, although it was only tested in simulations and for relatively serious faults.

2.7 Diagnostic strategies based on leakage inductance variation

For the moment, various diagnostic methods have been used, such as low-voltage impulse, FRA, and SCI for the recognition of mechanical defects in transformers. The disadvantage of these methods is that they are offline and the inception of a fault cannot be detected on time [90–93].

In recent years, the monitoring of the deformation of windings by the variation of the leakage inductance of the transformer has been gaining notoriety [94]. However, the main problem is that there is a certain error in the method of discrimination and precision, so it is not yet used in practice.

In [13, 94], the method for detecting the deformation of the windings by the variation of the leakage inductance or dispersion inductance is analysed. In [13], from the measurement of primary and secondary voltages, and the current of the primary winding, a least squares approximation of the dispersion inductance of each of the transformer phases is obtained. It starts from the equivalent circuit of the transformer to calculate the inductance, neglecting the magnetisation current. The developed model has the ability to be implemented online for the detection of the deformation of the winding efficiently. The accuracy in the identification of the parameter is satisfactory and can be improved by compensating the magnetisation current. The magnetisation current can exert an effective influence on the results. In addition, the proposed algorithm remains stable, which is not influenced by the load fluctuation or the change of its power factor.

2.8 Diagnostic strategies based on power monitoring

In [95], an online method to monitor the values of the most central transformer parameters (impedance, turn ratio, and power loss) is presented. Using a simple transformer model, it is possible to deduce the transformation ratio and the total winding impedance by linear fitting selected measured quantities as a function of the load. The internal power loss is simply obtained from the difference in power into and out of the transformer. It is possible to reliably detect changes of the size of 0.1% for most of these quantities which makes this method generally comparable in sensitivity to corresponding offline measurements.

Thus, the proposed method renders a possibility to continuously monitor the values of the transformer parameters online and thereby facilitates the early detection of a fault.

2.9 Diagnostic strategies based on no-load application techniques

In Section 2.6, current harmonics analysis techniques were presented through the use of the Fourier transform and wavelets transform [86, 87]. At the moment, these techniques are applicable only in conditions of no-load or low load of the transformer. Moreover, the approach is suitable for voltage harmonics within IEEE-specified limits and rated voltage application.

In [96], a method based on measurement of the variations of phase difference between the no-load input voltages and currents in the primary windings of power transformers is proposed. At the no-load condition, the transformer acts as a single winding with high self-inductance so that for most of distribution and power transformers, the no-load power factor averages ∼0.15 lagging [97]. Therefore, the transformer input current lags approximately the input voltage by an angle of 80°. If there is any turn-to-turn short circuit (even through a fault resistance) in one of the primary windings, theoretical and experimental results show that as the number of turns in short circuit increases, the input impedance angle (or the difference phase between voltage and current) decrease considerably. It is confirmed that for internal faults with a low number of turns (e.g. 1 turn, 2 turns), the equivalent impedance of faulty turns is mostly resistive. In other words, the compensating component in the current through the faulty winding is approximately in phase with its applied voltage. Although the method with load operation and with OLTC needs to be validated, it can be suitable for the no-load operation of the transformer.

2.10 Diagnostic strategies based on bushing monitoring

A special chapter deserves the bushings of the power transformers, which have a failure probability of 20%. Although the cost of these components is ∼0.05% of the value of a transformer, a fault can cause the service output, so monitoring of their status becomes relevant.

The diagnosis of the bushings is made by analysing the delta tangent and its percentage of variation or depending on its capacitance [98]. Diverse methods have been proposed for online monitoring of bushings. In [99], it is proposed to take advantage of high-voltage transients, such as over-voltages of lightning impulses, as stimuli for online dielectric spectroscopy of power transformer bushings. In [100], the possibility of applying dielectric spectroscopy to the bushings of the transformers and their limitations was analysed, obtaining favourable results. In [101], an online monitoring method is analysed to continuously estimate the variation of the capacitance and delta tangent of the bushing. The method is based on a measurement of high-frequency impedance in the bushing, whose variations reflect its state [102, 103]. In [104], the effect of contamination of the insulation and oil leakage of the bushings is analysed through online monitoring of capacity, tan delta, and partial discharges, being able to make a correlation between the monitored values and the condition of the

Table 11 Summary of different methods and their degree of detection

Ref.	Method	Detection degree	Observation
[45]	relay: increase in fluk linkage	more than 10% of the winding short circuited.	According to IEEE standard C37.91-2000 [41]
[54]	WT and neural networks	10% turns short circuited	Applied to two-winding three-phase transformers. Accuracy >98%
[94]	leakage inductance variation	radial displacement: 5.3% turns axial displacement: 18.2% turns axial displacement: 4.5% turns inter-turn short-circuit: 4.5% turns	Error in discrimination and precision method
[56]	relay based on ANN	5% turns of the winding and 1 turn to ground	It is not generalised
[34]	Park's vector	4% turns short circuited	There must be some failure resistance and it is not a condition of dead short-circuit
[35]	symmetrical components	3% turns short circuited	There must be some failure resistance and it should not be a condition of dead short-circuit
[71]	relay: symmetrical components	2.5% turns of the winding. Detection of a dead short-circuit condition (0.5% of turns)	Stability during overexcitation, inrush condition, and CT saturation
[68]	negative sequence current	2.27% of the winding and up to 1.92%	It does not depend on the load and system disturbances
[39]	negative sequence components	2% turns in dead short-circuit	Serious fault condition
[86, 87]	FFT and WT	2% turns short circuited and fault current up to 1 p.u.	Analysis with no-load or low load
[61]	relay: negative sequence currents	1% turns short circuited (4 turns)	Results not generalised (they treated a particular configuration and a single condition of the system)
[57]	fuzzy logic	1, 3, 5, 10, 15, and 25% turns short circuited	Simple and robust but requires expert criteria. Detects incipient faults in an early stage
[36]	negative sequence components	1% turns in dead short-circuit	Serious fault condition
[43]	adaptation of conventional differential protection	1% turns in dead short-circuit or more	It is not applicable to detect faults in the incipient stage
[58]	relay: negative sequence currents	1% turns short-circuited (2 turns)	Evaluated for different operating conditions, numbers of turns in short circuit, and different connections of the power transformer
[69]	neutral current of the primary side	4 turns short-circuited	Immune to supply voltage unbalance, constructive asymmetries, and instrumental errors and unequal distribution
[82, 83]	ΔV– I_1locus	2 turns short-circuited	Small variations make difficult to realise the fault
[96]	phase difference between U_1 and I_1	1 or 2 turns short-circuited	Applicable only with no-load (and low power factor). Next step: operation with load and with OLTC

bushing. In [105], an online method for capacitance and tan delta measurements of high-voltage bushings is presented, reaching a measurement precision similar to the offline tests. In addition, through the tap of bushings, the partial discharges inside the power transformer can be monitored, although more research is needed regarding the propagation of the DP pulses through the winding of the transformer and the effects of the distortion of the transformer. The pulses propagated far away from the site of the discharge activity (the attenuation and dispersion of the DP impulse waveforms are potentially significant) [106].

However, at present, with the online measurement in the HV bushings, the breakdown of the bushing dielectric and the transformer isolation system can be detected.

3 Discussion

Online power transformers monitoring is an increasingly widespread practice. The objective is to detect a fault in its incipient state and, as far as possible, estimate its severity and the remaining useful life of the machine.

The differential protection relays are a classical and robust protection and allow an online monitoring of the transformer. However, they are not able to identify inter-turn faults in an incipient stage with the strategies used at the moment nor displacements in windings or core columns. The FRA is an accurate method for diagnosing the mechanical state of the transformer; however, it has been implemented mainly offline and requires expert knowledge and sophisticated equipment. The possibility of online implementation of this technique, although it has already been proven, still does not offer an acceptable degree of reliability.

The DGA is able to detect any abnormality in the functioning of the transformer in an incipient state, both online and offline, although it is a costly method and is not applicable to dry insulation transformers.

On the other hand, windings resistance tests and partial discharges are widely used in power transformers. Although they offer the possibility of online implementation, the diagnoses obtained in those methods are not even comparable to those obtained through the offline application of the technique.

The evolution in the development of fault detection elements in power transformers was favoured from the use of digital differential protection relays. In these cases, it is easy to add new diagnostic routines that extend the original features from the variables that are monitored by the relay. This new possibility led to the development of new alternatives. Many of them have not yet been tested in real applications. Others have only been presented as theoretical proposals or applied in computer simulations. Other ones have been validated using laboratory prototypes.

AI techniques such as neural networks and fuzzy logic (which had already been used successfully in engines or generators) make possible to detect relatively minor faults. On the other hand, they have the advantage of requiring few input data and allow an online implementation.

The methods that use the Park transform or the symmetric components are capable of detecting faults through the

Table 12 General comparison of methods that use the analysis of electrical variables

Method	Ability to detect incipient faults	Necessity for expert criteria	Requirements	Computational effort	Type of fault Electrical	Mechanical
model-based strategies	some methods	yes. To establish threshold	parameters of the transformer	middle	•	•
artificial intelligence	some methods	yes. To design	training or expert rules	high	•	
use of symmetrical components	yes	no	no	middle	•	
ΔV–I locus	difficult discrimination	yes. To interpret	no	low	•	•
harmonic current content	some methods	no	no	high	•	
leakage inductance variation	difficult discrimination	yes. To establish threshold	parameters of the transformer	middle	•	
power monitoring	some methods	no	parameters of the transformer	low	•	
no-load application techniques	some methods	no	no	middle	•	

measurement of currents in an online manner, although their calculation and response time depends on the failure.

It should be noted that the methods of monitoring and detecting faults in power transformers by means of electrical variables (measurement of instantaneous voltages and currents) have the advantage of being applicable both to transformers immersed in oil and to dry insulation transformers. Furthermore, generally, these methods do not require any additional hardware installation since signals from the voltage and current sensors installed generally in transformers in service are used.Some of the most outstanding works cited are summarised in Table 11, comparing in detail the method used for the detection of faults and their degree of detection.

Table 12 shows a general comparison of the methods currently used for the detection and diagnosis of faults in power transformers through the analysis of electrical variables. From the point of view of the ability to detect slight short circuits between turns (1% of the total turns), it is observed that the proposals based on the monitoring of the negative sequence current are the most promising. On the other hand, some works based on AI are equally capable of detecting incipient failures.

Besides, from the point of view of the information required to implement a diagnostic procedure, it is observed that the techniques based on models require the original values of some parameters of the transformer, which constitutes a disadvantage. AI-based techniques, on the other hand, although they do not require data about the parameters of the transformer, need training stages or expert rules based on previous experience. Both alternatives, therefore, hinder its implementation.

The degree of development of most of the techniques listed in this paper is incipient. In effect, these are strategies that have been proposed and tested only at the level of simulations or in the laboratory. Therefore, it is very difficult to determine which have the greatest potential and the possibility of imposing on the rest. However, it is possible to affirm, without doubts, that these techniques are being consolidated and offer a useful complement to traditional techniques.

4 Conclusions

The development of digital measurement and protection systems for transformers has opened up the possibility of redesigning the detection and fault diagnosis strategies. Many alternatives have been presented for this purpose during the last years. Some of them try to apply techniques that have been previously tested in other electrical machines (motors or generators) such as EPVA or current analysis in the frequency domain. In other cases, strategies based on models are proposed, which have shown great capacity in many industrial applications. Some authors use the negative sequence components to monitor the transformer status.

These new alternatives are in development and present a great growth potential due to their online implementation, their low cost, and the speed to detect anomalies.

In the case of the techniques that are presented as variants to the traditional differential protection, the challenge remains to increase the sensitivity of the relay avoiding incorrect operations during inrush transients or external faults.

Although the techniques analysed here are not able to replace the traditional ones, they are a very useful complement to improve the usual maintenance practices in power transformers.

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