REVIEW ON INVESTIGATING THE FAILURE OF POWER TRANSFORMER AND ITS MITIGATING STRATEGIES

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Abstract — **One of the most relevant electrical energy transfer components in the power system industry is the power transformer. The reliability and security of the safety of the power transformer is paramount for system operation and controls. Ageing, over- voltages, over fluxing and the occurrence of prevailing faults in the power transformer needs critical attention to prevent the power transformer's poor efficiency, failure and explosion. The various mitigation techniques for tackling those power quality issues are also considered and discussed in this paper.**

Keywords — Over-voltages, Insulation, Flux, Ageing, Deterioration, Power Transformers.

I. INTRODUCTION

In a power system, power transformers are critical and costly elements. Large power transformers are considered to be a major and very costly electrical power system asset. There are virtually no moving parts for power transformers, except tap changers or cooling fans that are used to transform power (voltage and current) from level to level. Therefore, the copper windings, laminated cores and manufactured parts can last forever, like rotating machinery with sufficient corrosion safety. However, "insulating materials, primarily made from cellulose materials, deteriorate due to the effects of temperature, humidity and oxygen" [1]. It is the temperature that must be maintained within established limits to avoid rapid decay under normal use to the point of failure that the human standard can be very long [1].

Normally, "the life of the transformer depends on the life of the insulation" [1]. The" life of the transformer shortens when insulation fails" [1]. "The life of the transformers gives an impression as if it was very certain, but a transformer hardly explodes in fact" [1]. Typically, it is an uncommon stress that breaks down a damaged point, leading to the transformer's destruction [2]. There are several variables leading to a power transformer failure, but it is grouped into two categories; "Deterioration of insulation with temperature, humidity and oxygen over a period of time, and operating stresses, mechanical, electromagnetic, thermal beyond the strength of those parts of the power transformer that have substantially deteriorated over a period of time to be addressed in this paper" [1].

II. DETERIORATION OF INSULATION

The life of transformer shortens when probably "its failure becomes predominantly too high. It is practically impossible to determine the probability that any transformer will fail within a few days, months or years; but this probability actually exists" [3]. "In other words, it is not possible to predict precisely the life of a transformer working operations under a given temperature and load condition" [3].

Once the insulating materials have become brittle and cracked, the dielectric strength of the insulation soaked in oil does not deteriorate and "it is also possible for a transformer to continue to work even after the mechanical life of its insulation has been variable, unless it is subjected to successive mechanical stresses, such as short circuits or other mechanical shocks" [3]. It's known to power engineers that many times a transformer which has been giving satisfactory service for years, when shifted to other location can due to damage of its weakened insulation. It does not follow; therefore, when its insulation becomes brittle, a transformer can fail [3]. However it's subjected to successive stresses.

2.1. Ageing of Insulation.

The key insulation types in the oil-immersed transformer, paper or cellulose material along with oil.The insulation must therefore preserve its acceptable dielectric strength against voltage surges and ample mechanical strength against short-circuit events.

When heated under oil, "paper and press board insulation loses its mechanical strength for a long period of time, but dielectric strength is hardly affected until the paper is charred to the point where free carbon, survive mechanical shocks, it becomes conductive or too brittle" [14]. Deterioration to this degree is complicated by decomposition-liberated free water, leading to a decrease in the dielectric- strength of the insulation. Insulation depolymerisation takes place as degradation sets in. Therefore, as this happens, the mechanical strength will

be considerably diminished. There are many ways of defining the mechanical strength of an insulating paper, but the quantity based on its tensile strength is the most important and simple to calculate. While there is no simple link between loss of tensile strength and loss of productive life of the transformer, it seems rational and logical to use tensile strength loss intermittently as a measure of a transformer's life.

2.2. Causes of Loss of Tensile strength of paper in oil

A mixture of factors, including temperature , time and presence of moisture , oxygen and various other reactive materials in the oil, to which paper insulation is exposed while in use. In the past, several studies have been performed that provide fair closeness to the link between tensile strength, temperature and time. It was, however, found that very small amounts of oxygen with moisture would lead to different types of temperature-dependent reactions and presence of catalyst in the insulating materials.
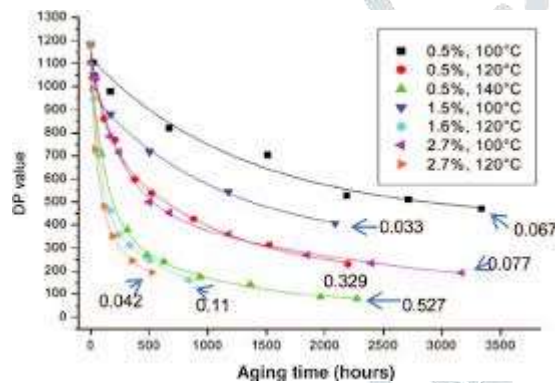

Figure1: Effect of moisture on mechanical strength of oil-immersed paper [4].

Figure 1 provides a simple plot of the many ways in which paper mechanical strength can be described. The combination of the factors under which temperature, time, presence of moisture, oxygen and other reactive materials are subjected under paper insulation.

2.2.1 Law of insulation Ageing

A "transformer's insulation appears to age and deteriorate when heated" [4]. "The higher the temperature, the quicker the degradation of the insulation of the transformer" [4]. The loss of life of the insulation would be below average conditions during times of subnormal operating temperature. As a result, the transformer could have worked safely at above normal temperatures for a time; given the loss of insulation during the course of operation this period. At a temperature lower than that, it is properly compensated for by operation for a sufficiently long time.

Depending on the temperature at which it runs, the insulation deteriorates and loses its life. It is therefore important to consider the various factors that lead to the degradation of insulation, in particular the temperature and legislation relating to the ageing of insulating

materials, so that the transformer can be used optimally without rapid losses in the power system; resulting in premature failure.

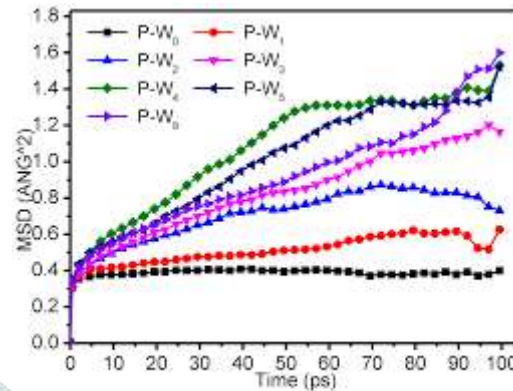Effect of moisture on mechanical strength of oil-immersed paper.

Figure 2: Ageing Insulation of transformer [4].

We can understand from equation (2) that this law can be expressed in a more convenient form called the relationship of Mont singer in the range of 80 to 140 degree winding hot spot: Life= e^{-po}

Where, p = constant
O = temperature

Here, "the rate of loss of life due to ageing of the transformer insulation doubled with every 6 degree temperature rise" [2]. Isolation ageing was based on the 8 degrees Celsius law until a few years ago, which was replaced by 6 degrees Celsius. Under different temperatures, consider the actual behaviour of cellulose insulation more closely.

The Mont singer relationship can be used at rated load and reference ambient and temperature rise conditions to obtain the relative rate of life usage at any hot-spot temperature over the usual hot-spot temperature; relative rate of life usage;

$V = \dfrac{\text{rate of using life at any hot- spot } 0c}{\text{Rate of using life at rated hot- spot } 0cr}$

$= 2(0c- 0cr)/6$

$= 2(0c – 98)/6$

Or $0c = 98 + 19.93 \log_{10} v$

If a hot-spot transformer of 0c uses the life of one day in no hours:

$t= 24/v$
$= 24 * 10^{(98 – 0c)/19.93}$.

III. MITIGATION TECHNIQUES OF INSULATION DETERIORATION

Isolation resistance experiments are carried out in order to determine "insulation resistance from individual windings to the ground or between individual windings, Insulation resistance tests are usually measured in mega ohms directly or can be calculated using measurements of applied voltage and leakage current" [5]. The preferred approach for calculating I.R is that the tank (and the core) is always grounded [5].
Between any winding and all other windings grounded, resistance measurements are then made.

3.1. Insulation Resistance Testing
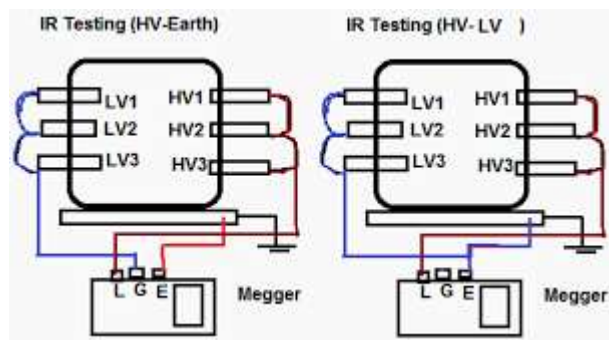
Figure 3: IR testing of HV- Earth and HV – LV [6].

For IR measurements, transformer windings are never left floating. "In order to calculate the IR of the winding, solidly grounded winding must have the ground removed in another" [6]. Whether the land can be weighed, treat it as part of the circuit's grounding portion.

3.1.1 Steps to measure the transformer's IR;

- Put off and detach the lightening arrestors and jumpers from the transformer.
- "Discharge the winding capacitance
- Thoroughly wipe clear the bushings and the windings also short circuited" [6].
- Guard the terminals in order to remove any exterior leaks over terminal - bushings.
- Record the temperature difference
- Link the probes for testing and check for continuity.
- Check voltage and readings for nodes are applied. The "IR value at 60 seconds after the test voltage has been applied is called the check temperature as the IR of the transformer" [6].
- Neutral bushing for the transformer during the test must be disconnected from the ground.
- Both LV surge diverter earth connexions during the test are to be disconnected.
- Because of the transformer's inductive properties, the IR reading must "not be taken until the current of the test stabilizes" [5].
- Stop "meggering when under the vacuum of the transformer" [5].

We can observe that;

- HV – Earth 200Mega ohms
- LV – Earth 100Mega ohms
- HV – Earth 200Mega ohms

3.1.2 Factors affecting on Insulation Resistance of Transformer

The transformer's IR values are influenced by:
- Terminal bushing surface condition
- Oil consistency.
- Quantity of Insulation Winding
- Oil temperature

Application length and sense of the test voltage.

3.2 Fourier Transform of Transformer Windings.

Quick Fourier conversion is the process which calculates discretization of Fourier conversion efficiency.
The expression describes the Fourier integral;

$$S(f) = \int_{-\infty}^{+\infty} S(t)\, e^{-j2\prod ft}\, DT.$$

At one particular frequency of interest, this approach isolates a peak. But if "two pure oscillations occurring at two adjacent intervals are constructed from the signal, two peaks are obtained without localization in time" [7].
"The transfer function of trans-admittance magnitude is obtained by dividing the neutral current transform by the applied impulse voltage transform" [7] for the Fast Fourier transform analysis.
"This function of transfer, the ratio and the results obtained in the frequency domain, characteristically defines the transformer 's behavior and is therefore independent of the input signal" [7] used.

3.2.1 S (f) Experimental Power Transformer Research, The Fourier Transforms.

The descriptions "of the transformer used and the modified experimental method are illustrated below" [14]:

Transformer Definition;-

Power rating of 61MVA and the voltage rating of 11.5/230KV is "Generator transformer and test design used for testing. The high voltage winding consists of the construction of two groups with the centre entry type containing a total of 112 discs" [14]. Half of "the windings are used for scientific experiments due to symmetry alone" [14].

Application of Recurrent Surge;-

The windings are added to the RSG form of low voltage pulse with a peak magnitude of 100 volts. The RSG parameters are adjusted so that it achieves the necessary 1.2/50μ input wave form. The "neutral end of the high voltage winding is connected to Earth through a non-inductive 20 ohm resistor shunt" [7].
Using a digital storage oscilloscope made by Nicollet, the "input voltage and output neutral currents are measured simultaneously" [7]. For the purpose of carrying out the experiment to "provide access to the bare copper conductor of the discs, the paper insulation from the outer twin of each disc in the winding is removed" [7].The "bare portions of the conductors were physically stored in order to make the disc short, and corresponding neutral currents were registered" [7].

Schematic diagram test set up is shown below;
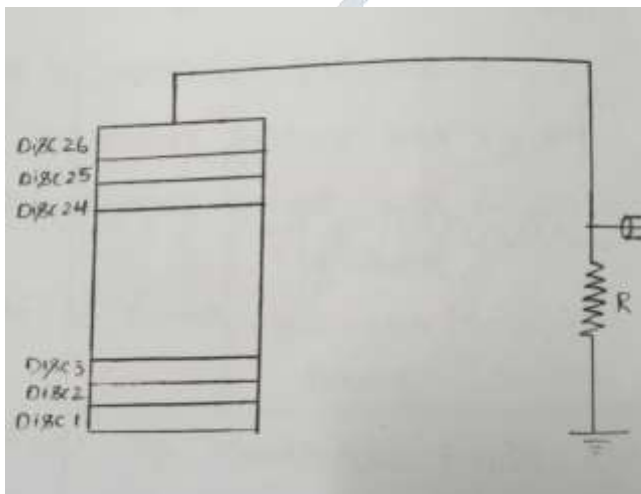
Figure 4; sub – dividing windings in various discs

Sub-windings are broken down "into large numbers of components. Self-inductance, mutual inductance and capacitance, parameters with"[7] the same windings in all the other sections and also with other windings, are described in each section.
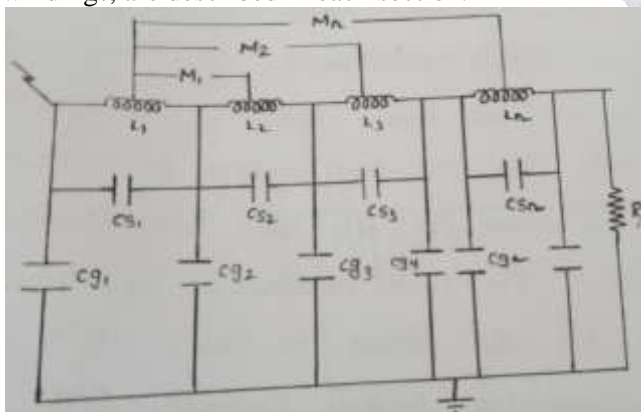
Figure 5; An Equivalent electrical network

From the equivalent network of figure 5; where,
L1, L2…….Ln = Self inductance of each section

M1, M2…...Mn = Mutual inductance.

CS1, CS2….CSn = Series capacitance of the section.

CG1, CG2….CGn = Capacitance of the section to ground.

RSH = "Shunt resistance, for neutral current coupling" [7].

For re-coding neutral current for short discs, the following instances were considered.

Sanitary winding (with no defects)
- "2-4 discs shorted
- 2-6 discs shorted
- 2-10 discs shorted
- 2-12 discs shorted
- 2-14 disc shorted
- 2-16 discs shorted" [7].

Observations:

"Changes in any one of the winding parameters will change the frequency response characteristics of the neutral currents"[7]. For secure and "winding faults with 2-4 discs" [7], below are the typical neutral current wave types:
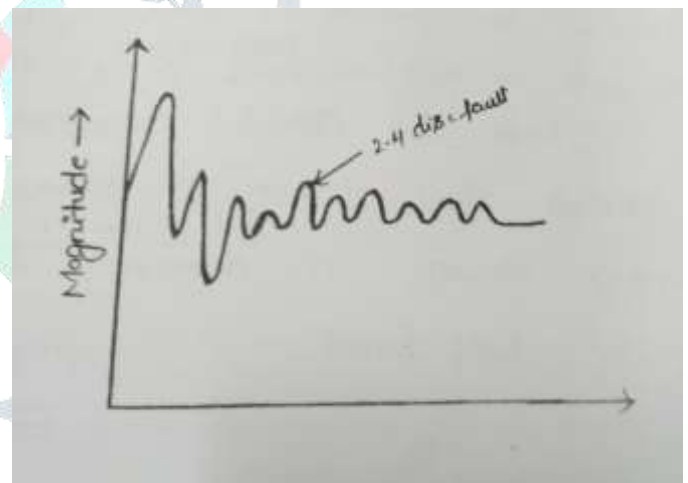

Figure 6; winding with 2- 4 discs

Figure 6 is translated into data from ASCII. In order to achieve equivalent time intervals for comparison, the reported acquisition is kept the same during the experiment.

The "Fast Fourier transform was calculated for the neutral currents for healthy winding and winding with faults to achieve dominant frequency peaks" [7].

The change in dominant frequencies is shown below for safe winding and winding with various faults:
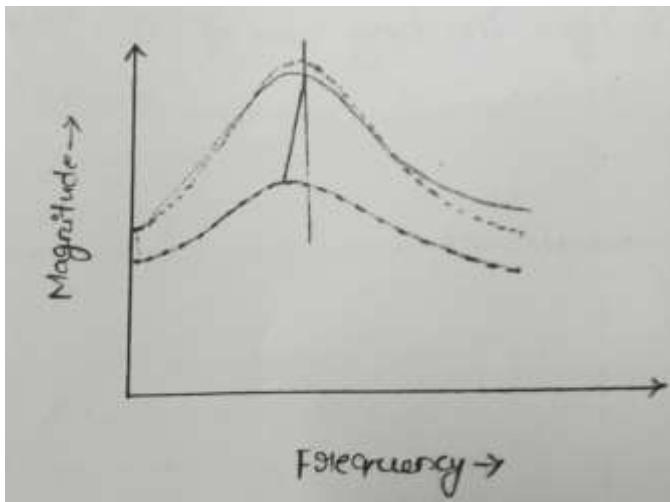
Figure 7; winding with different faults

From the careful study of Figure 7 above, it is shown "that the percentage-shift in dominant frequencies with respective disc" [7] faults has a clear pattern.

3.3 Winding Movement On The Basis Of Frequency

"For the identification and location of winding motions and mechanical deformations in both axial and radial coils, study of the frequency domain technique is studied and movements of power transformers" [8]. The architecture, methodology and approach are also discussed. The "development algorithm is based on the use of distributed S-domain parameter by an analogous network which is cascaded with other parts to constitute a generalized model" [8]. "The frequency domain transfer admission is used as the key definition in order to describe and locate the winding motion and deformation" [8]. "It is suggested to measure and store the transfer admittance over the frequency range 0-10MHZ region in normal activity data stored for comparison with the corresponding data during failure" [8].

Importance of FRA for the detection and location of winding faults and movements, damping pressure loss, and insulation ageing can be defined as a result of "faults or external mechanical damage" [8].

In an important analysis of Artificial Neutral Networks, frequency response measurements were effectively used to estimate the transformer. Example: open test of circuits; Focusing on the winding mechanical motion to determine the condition of the transformer later in the diagnostic process. The analysis test is based on the identification of the coefficient of correlation obtained by "comparing the FRA data from the winding test with the second reference measurement package" [8].

The identification of the winding movement is "based on extending the FRA's high frequency range up to 10MHz" [8]. "It can introduce both minor axial and radial winding movements at specified locations along the winding, as well as possible changes in winding damping pressure" [8].

Impact of movement of axial windings

In Figure 8, this is "simulated by changing the value of the 'c' series capacitance" [8]. "For one disc, at different places, a^10 change in that value will be tested" [8]. "By adjusting the distance to Xn, you can do this" [8]. "The analogue circuit showed 7 shows that Xn1/40 suggests that this axial movement takes place at the windings" [8]. "Neutral terminals that raise Xn from 0 to 67 will reduce the change in the direction of the winding axial deformation towards the winding terminals" [8].

10 % drop in the sequence of the capacitance
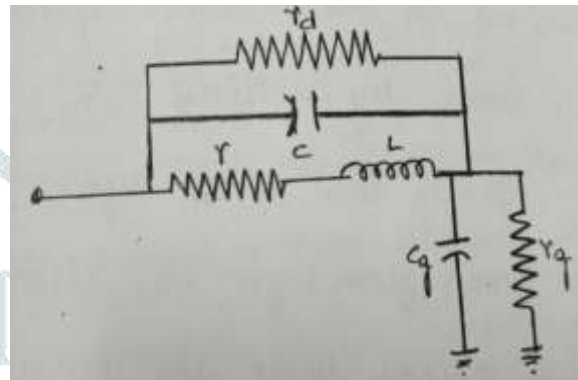
Figure 8; Series capacitance

This is accomplished by settling FN 1/41 with the capacitance of the sequence 1 / n 1/40 whilst Xn represents the "distance from the neutral point to show the one-disc transition" [8].

In the base case, Freq (originally 7.35MHZ), "depending on the direction of the winding motion, is a maximum of 2KHZ" [8]. Nevertheless, "it has been found that their initial 9.527MHZ frequency is more sensitive to the location of the disc and is increased by up to 6 KHz" [8].
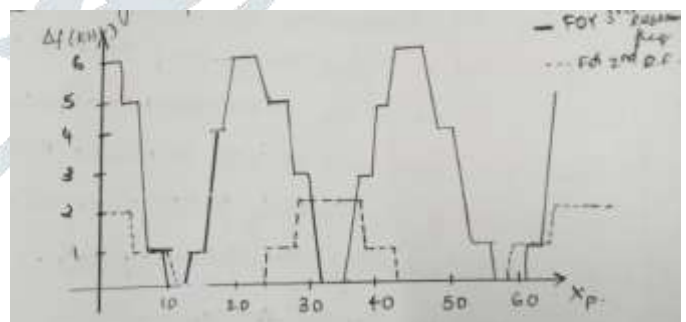
Figure 9; Frequency increase in the series capacitance [8]

10% capacitance "in series, by setting FN 1⁄4 1 with a series capacitance of C1⁄4 5.61 Power factor, this is done to reflect the change in one disc" [8]. Just "as is seen from the figure above. The derivation of frequency is ve, which means that it has decreased all resonance frequencies" [8]. "The first frequency resonance can be observed because of an increase in the series capacitance 'c'. Furthermore, the values of these frequencies respond to a 10% rise in 'c' relative to the figure as seen" [8].
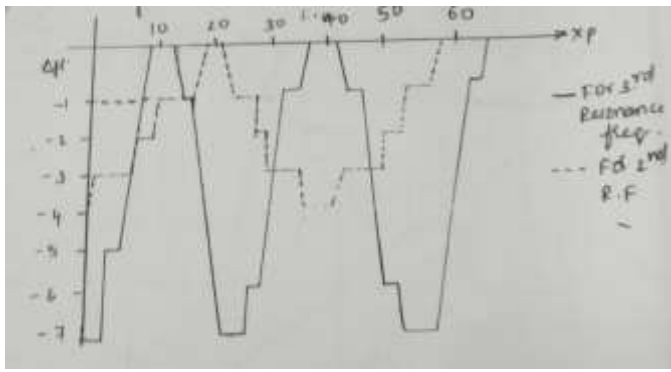
Figure 10; Frequency of maximum deviation

As seen from the figures (9&10), the highest "deviation was the 3rd resonance frequency that would occur due to motions at certain places" [8]. "This suggests that a more reliable criterion for the detection of axial winding motion would be the use of 3rd resonance frequency changes" [8].

Due to the minor influence of neutral resistance, the $Xp1/4$ 33 values, thus; the "winding middle point" [8], are almost symmetrical in Figure 9 & 10. "The largest deviation in the third resonance frequency will occur at $Xn1/4$ 21, corresponding to disc number 22, as shown in the figure above. From figure 10, it can also be seen that the 3rd resonance shifts" [8].

The Radial Winding Movement Effect

   This "can be done by altering the value of ground capacitance Cn. Two cases are present, as examples of the effect of radial winding movement" [8].

10 percent rise in "ground capacitance Gc;
By setting Cn 1/4 0.123Pf to Fn 1/4 1 and by adjusting the distance between Xn 1/4 0 and Xn 1/4 66 as the neutral point" [8].

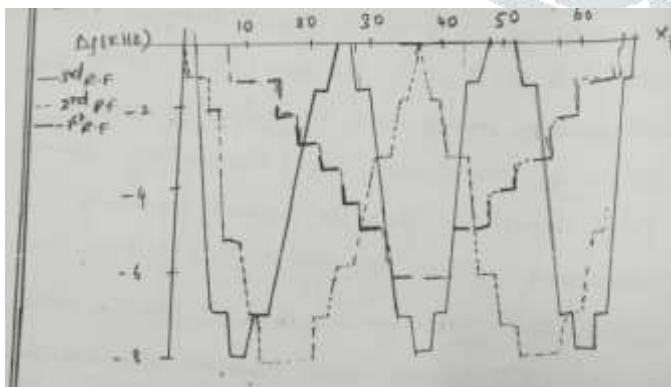*Figure 11;* Frequency with distance change from neutral point

A decrease in ground capacitance Cg of 10 percent;
"To reflect the radial movement of the winding disc, the ground capacitance is set to equal Cn 1/4 0.108Pf, as done in the previous case" [8]. The "efficiency shown in Fig. 11, is such that that the deviation in the resonance frequency is reversed by the symbol" [8]. As noted, "both axial and radial movements can result in resonance

frequency deviation of both + ve and -ve, and it is important to investigate whether the shift in frequency can eventually be masked by simultaneous axial and radial movement. It is to be noted in Fig. 8, 9, 10, and 11 that for the same discs displaying the minimum frequency deviation due to radial winding movement, the maximum deviation of the 3rd resonance frequency due to axial motion occurs. An intermediate position Xn 1/4 18 is therefore chosen to verify these parameters, so that simultaneous axial and radial disc movement can lead to observable deviations in the 3rd resonance frequencies. The capacitance of the series remained fixed with a 2.10 percent adjustment. The change in ground capacitance ranges from 10 to 20 per cent. This implies varying the radial movement percentage while keeping the axial movement constant. The almost linear plot shows that the shift in the third resonance frequencies results from a 10 percent reduction" [8] in 'C' and a rise of about 20 percent in Cn at the same time.

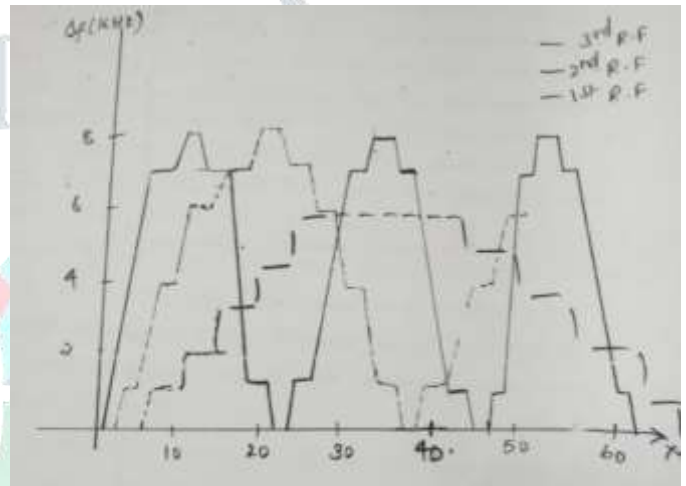*Figure 12;* Simultaneous reduction of C and Cn

The "approach for frequency domain analysis presented for the identification and location of the transformer winding movement is introduced" [8]. "It is focused on monitoring of the winding transfer admittance frequency spectrum and 10MHZ" [8].
The technique can handle the winding coils for both axial and radial movement [8].

IV. OVER VOLTAGES

   In "the power system, the production and breaking of electrical circuits with switchgear may result in abnormal over voltages with high inductances and capacitances" [9]. Over voltages can "go as high as six times the voltage of the standard power frequency" [9].
   "Switching effect with a high voltage rate in circuit breaking operation may cause frequent restriking of the arc between the contacts of circuit breakers, causing current leakage that can energise the power transformer" [9].

4.1. Over voltages due to Switching Surges

"High natural frequencies of the device, a damped normal frequency voltage portion, can involve switching surges" [9]. With successive reflected waves from terminations on the restricting and recovery voltage of the device.

4.2. Characteristics of Switching Surges

i. Switching surge wave shapes are very different and can come from any of the following sources;

ii. Transmission line de-energisation, cables, shunt capacitors, capacitor banks, etc.

iii. Unloaded transformer disconnections, reactors.

iv. Energisation or reclosing of reactive loads and lines

v. "Sudden Load Shutting Off-.Short circuits and fault clearances

vi. Resonance phenomenon like Ferro-resonance" [9].
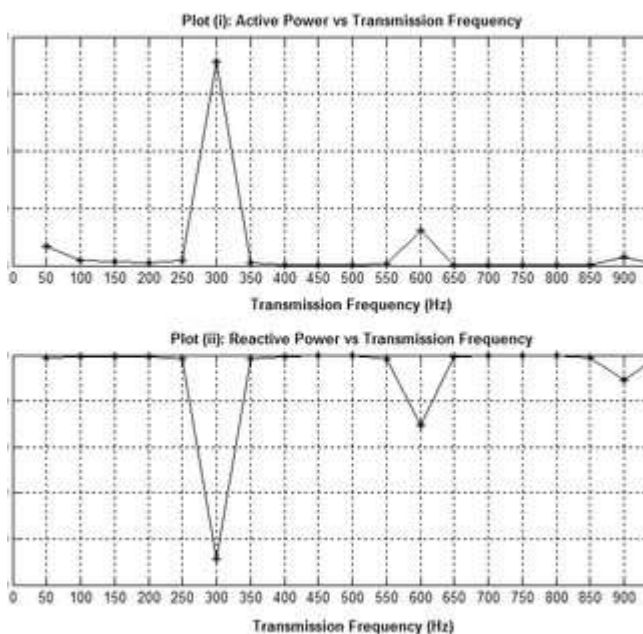
Figure 13: Block diagram for energisation of long power lines [9].

It is evident from Figure 9, "the switching surges that over voltages are irregularly oscillatory or unipolar and can be with harmonics of high frequency or power frequency" [9]. In "the case of transformer energisation, the relative magnitudes of the over voltages can be approximately 2.4pu and 1.4 to 2pu in the transmission line switching" [9].

4.3. Over voltage due to Lightning Impulses

The phenomenon of "lightning is a peak discharge in which the charge accumulated in the clouds discharges into an adjacent cloud or field. The separation of electrodes, i.e. cloud-to-cloud or cloud to

ground, is very wide, maybe 10 km or more. Too many and unknown are the variables that contribute to the creation or accumulation of charge in the clouds, but positive and negative charges are divided during thunderstorms by the strong air current with ice crystals in the upper part and rain in the lower parts of the cloud. This separation of charges depends on the height of the clouds, varying from 200 to 10000 m, with their centres of change likely to be around 300 to 2000 m away. The amounts of the clouds involved in the lightning flashover are unknown, but the charge inside the cloud may be as high as 1 to 100 c. Clouds can have a capacity as high as 10^7 to 10^8V with field gradients ranging from 100V / cm within the cloud as high as 10kv / cm at the initial discharge stage" [10].

The energy of cloud discharges can be as high as 250kwh.

Therefore, if the discharge point is the power transformer, it is evident that if not well secured, the transformer will be energised.
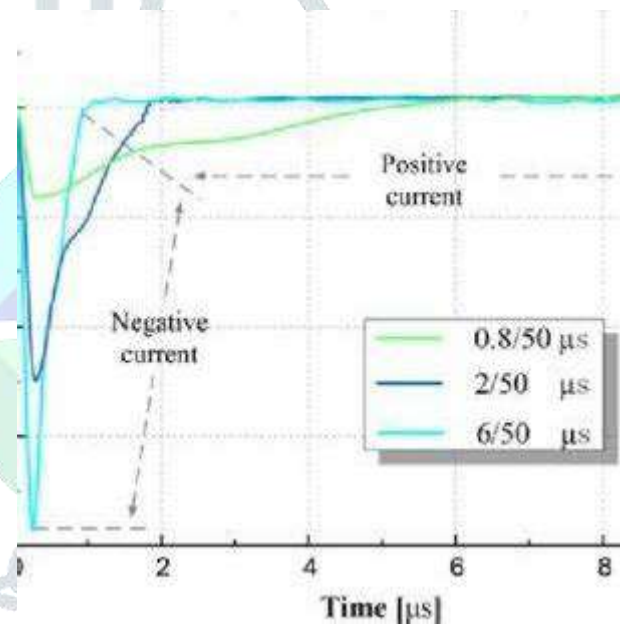
Figure 14: Volt-time characteristic of the voltage of lightning [11].
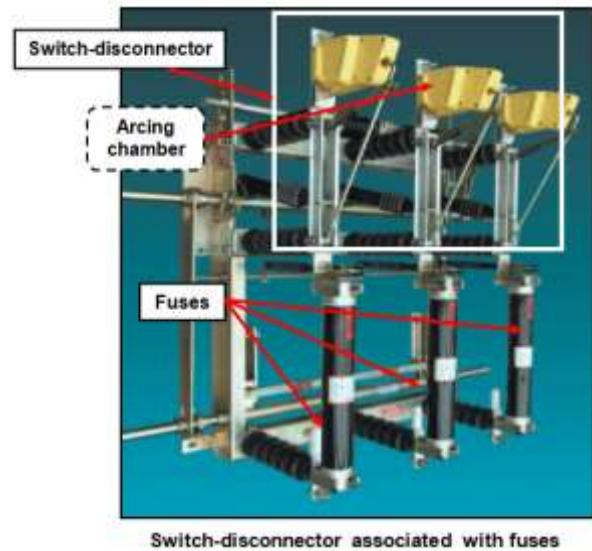
Fig.10. a similar pattern is shown by the measured current, which "also consists of the negative part and the positive part, with the simulation result. However, it is important to note that the maximum value of the calculated current is lower than that of the simulation performance. For example, in the 2/50 μs condition, the maximum value of the measured current is -1.25 A, while the dielectric current in the simulation outcome is -3.04A" [11]. In the same condition the value of the outcome of the simulation is approximately 2.5 times that of the test results [11].

V. MITIGATION TECHNIQUES OF OVERVOLTAGES

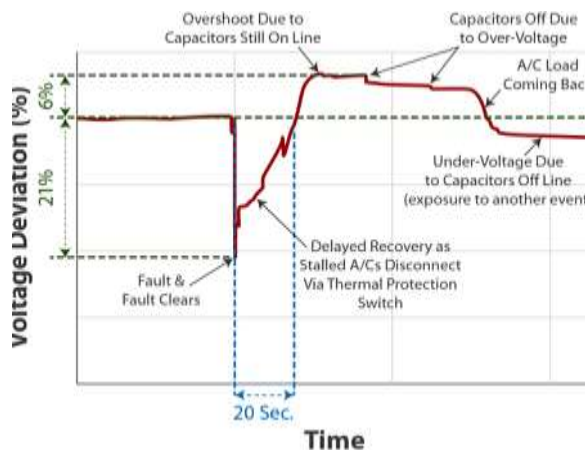### 5.1 Induced Fault Delayed Voltage Recovery

"Induced Fault delayed voltage recovery (IFDVR) refers to an unexplained pause after normal fault clearance in restoring the voltage's nominal value. Initial findings of these delays in the western interconnection by utilities led to concerns that significant cascading blackouts could be precipitated" [12].

"The FIDVR initiative sought to identify the physical processes that caused the delay, to evaluate the risks presented by the delay and recovery to the reliability of the power system, and to identify corrective measures, if remedial, to manage these risks" [12].

Figure 11: voltage deviation and time curve [11].

5.2. Good Configuration of Protective Devices.

In order to signify the fusion and to provoke the three-pole opening of the switch-disconnect, fuses must have a mechanical latch or to prevent the installation from working only in two phases.

Manufacturers provide tables to pick a fuse's rated current, taking the rated voltage and power into account, as per IEC requirements.

Switch-disconnector associated with fuses

Figure 12: Switch-disconnector associated with fuses [13].

In these circumstances, "to enable the built-in transformer safety to take effect, the switch-disconnector must be fitted with a tripping coil" [13].

VII CONCLUSION

As discussed in this review paper, its obvious there many factors that can affect the life span of the power transformer as delicate equipment in the power system. These factors; insulation deterioration, residual faults occurrences amongst others directly have a great impact on the transformers life is discussed.
Different mitigation strategies based on this study are also discussed and some optimal methodologies have been created.

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