World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:18, No:7, 2024

Protection of Transformers against Surge Voltage

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***Abstract*—**Surge voltage arises in the system either by switching operations of heavy load or by natural lightning. Surge voltages cause significant failure of power system equipment if adequate protection not provided. The surge arrestor is device which is connected in a power system to protect the equipment against surge voltages. To protect the transformers against surge voltages, metal oxide surge arrestors (MOSA) are connected across each terminal. The Basic Insulation Level (BIL) of transformers has been defined in the national and international standards based on its voltage rating. While designing transformer insulation, factors such as BIL, surge arrestor ratings, and its operating voltage have to be considered. However, the performance of transformer insulation largely depends on the ratings of the surge arrestor ratings, their location, the margin considered in insulation design, the quantity of surge voltage strikes, etc. This paper demonstrates the role of surge arrestors in protecting transformers against overvoltage, transformer insulation design, the optimum location of surge arrestors and their connection lead length, insulation coordination for transformers, the protection margin in BIL, and methods of safeguarding transformers against surge voltages in detail.

***Keywords*—**Surge voltage, surge arrestors, transformer, protection margin.

I. Introduction

DISTRIBUTION and power transformers installed in power systems are frequently exposed to overvoltage caused by lightning strikes. Transmission and distribution system MOSA are widely used for protection against surge voltage. However, lightning strikes are still one of the major causes of transformer failure in the network [3]. Such failures can cause interrupted power supply and make a system unreliable. Electricity consumers continue to demand improvement in supply reliability as well as power quality. A surge arrestor is a device designed to protect electrical apparatus from transient voltage, and to limit the duration and amplitude of follow-current [3]. Surge arrestors are connected to the system between the phase conductor and earth. When a MOSA is subjected to a surge from the system to which it is installed, it responds by shunting the surge current, thereby limiting the overvoltage on the protected equipment [2].

Origin and Classification of Surge Voltages

Voltage stresses are generally classified based on parameters like duration of the power-frequency voltage or waveform of an overvoltage according to their effect on the insulation or on the protective devices [5]. Such voltage stresses within these classes have several origins, including temporary overvoltage (TOV), Switching Impulse Overvoltage (SIV, or slow front overvoltage, SFO), lightning overvoltage (LIV, or fast front overvoltage, FFO), and very fast transient overvoltage (VFTO) [5].

A. TOV can originate from various sources including system faults, switching operations of light load such as load rejection, resonance conditions, and ferro-resonance, among others.
B. SIV can originate from various sources such as system faults, switching operations of heavy load (Line energization for long or medium transmission lines), and similar events.
C. LIV originates by natural lightning strikes, either directly on transmission line shield wire or phase conductor, known as direct lightning strokes, or indirectly through nearby strikes).
D. VFTO can originate from faults or external flashover across insulators or bushings.

Up to about 300 kV, the highest voltage stresses arise from lightning impulses. Whereas, in systems above 300 kV, the importance of switching impulses increases, reaching a point at about 400 kV where they are equivalent to lightning overvoltage. The relationship between per unit (p.u.) voltage and the duration for different kinds of over voltages is shown in Fig. 1 [5].

The BIL of the transformer must be capable of withstanding all types surge voltage, at least up to the response time of protective device.

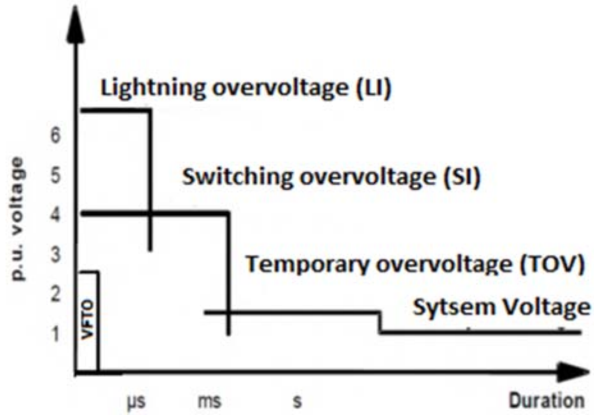

Fig. 1 Magnitude and duration of surge voltages

This paper discusses in detail the requirements of transformer insulation levels to withstand surge voltages, the role of surge protective devices, and insulation coordination for transformers.

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II. Design Criteria for Insulation Level of Transformer

Transformer insulation is designed as per the rated voltage and required BIL. This includes inter-turn insulation of high-voltage (HV) and low-voltage (LV) windings, as well as the main insulation between HV and LV windings, and between HV and LV windings to earth. The protective level of a surge arrestor is defined based on insulation coordination standards defined in IEC 60071-1 and IEC 60071-2. The selection of insulation strength is aligned with the expected overvoltages to obtain an acceptable risk of failure [4]. The degree of coordination is measured by the protective ratio (PR) which is represented as:

$$Protective\ ration = \frac{Insulation\ Withstand\ Level}{Voltage\ at\ protected\ equipment} \quad (1)$$

The BIL of a transformer is defined as the voltage it can withstand for one minute withstand voltage and the peak voltage of a 1.2/50 µs wave without experiencing insulation failure. The waveform of a 1.2/50 µs surge indicates that it reaches its peak value within 1.2 µs and decays to 50% of the peak value within 50 µs. Transformers rated above 220 kV voltage, or in applicable cases, those subjected to switching impulse voltage, are also defined by their BIL, along with LI voltage. For insulation coordination, protective ratios are calculated at three separate points within the volt-time regions. These are switching surge withstand (if applicable), the full wave withstand and the chopped wave withstand. The protective ratios must be met or exceeded if satisfactory insulation coordination is to be achieved [3]. As the steepness of surge current increases, the arrestor presents higher residual voltage, thereby reducing the protective margin which endangers the life of the transformer [3]. Hence, while designing the BIL of transformer insulation, all of the above basic principles should be considered. The procedure of designing transformer main insulation and inter-turn insulation depends on rated voltage and highest system voltage. The corresponding required standard rated withstand voltages against surge voltage characterize the insulation of the transformer. The step-by-step procedure to determine the required minimum BIL is defined below:

a. System analysis consisting of continuous power frequency voltage.
b. Overvoltage, its origin, classification of stressing voltage, and the protective level of over voltage limiting device. Overvoltage is assumed to produce the same dielectric effect on the insulation as the overvoltage of a given class occurring in service due to various origins, including internal like TOV or SI and external like LI.
c. Determination of the co-ordination withstand voltage, the insulation characteristics, and the performance criteria (the basis on which the insulation is selected such as it is economically viable and operationally at the acceptable level) [1].
d. Coordination withstand voltage (U_{cw}) for continuous operating voltage refers to the withstand voltage value of the insulation configuration under actual service conditions that meets the performance criterion.
e. Altitude correction factor/atmospheric correction factor includes the altitude correction factor (K_a), atmospheric correction factor (K_t), transformer test assembly, and quality of Insulation.
f. Required withstand voltage (U_{rw}) refers to the test voltage that the insulation must withstand in a standard withstand voltage test. This ensures that the transformer insulation will meet the performance criterion when subjected to a given class of overvoltages in actual service conditions and for the whole service duration.
g. Selection of rated withstand voltage (U_w) involves determining the value of the test voltage applied in a standard withstand voltage test. This test proves that the provided insulation in the transformer complies with one or more required withstand voltages.

The standard rated withstand voltage is given in Table I [4].

TABLE I
BIL of Transformer

Highest voltage for equipment, kV (RMS value)	Standard rated short duration power-frequency withstand voltage, kV (RMS value)	Standard rated lightning impulse withstand voltage, kV
3.6	10	40
12	28	75/95
36	70	170
72.5	140	325
145	230/275	550/650
245	460	950/1050

III. Protection of Transformer Against Surge Voltage

The problem of protecting transformers against surge voltage requires consideration of several important factors, which include the following:

a. Magnitude and nature of the system overvoltages.
b. Impulse or lightning impulse withstand strength of the new or used transformers.
c. Voltage characteristics of the protective device.
d. Lightning voltages which may reach the transformer terminal.

The principal overvoltages cannot be predicted accurately in terms of magnitude or its characteristics if no protection or limitations are applied. The ability of transformer insulation in oil to withstand lightning surges is independent of the polarity of voltage that is positive or negative. However, it depends on the rate of rise of lightning surge voltage, its magnitude and duration [6]. Furthermore, a transformer may be subjected to overvoltage several times within one second or so as a result of multiple or repetitive lightning strokes.

IV. Methods of Protection of Transformers Against Surge Voltage

Interception of Direct Strokes

With sufficient information about the power system overvoltages and the characteristics of natural lightning, it is possible to provide means of intercepting direct lightning strokes. This is done by preventive direct lightning strokes coming in contact with the phase conductor except in rare cases. Such protection is achieved by installing shield wire or shielding of transmission lines or substations. The popular method of intercepting lightning strokes is by means of a ground wire. The ground wire is placed above the transformer that needs to be protected. The grounding resistance of the wire is kept as low as possible to prevent the potential of the ground wire or the supporting structure from becoming high enough to cause back flashover from structure to phase conductor. The ground wire can be placed over the substation, over the transmission line, or both locations. Another method of intercepting the direct strokes is to erect a mast or multiple masts on the top of the substations to adequately shield them. In this type of protection, the mast must be high enough to adequately shield the transformer or system under consideration.

Lightning Arrestors

Lightning arrestors are most generally used for the protection of transformers against surge voltages. When lightning or other interferences cause high peak currents or voltages in an electrical circuit, these arrestors rapidly transition to a low-resistance state and discharge instantaneous energy to the earth. As a result, surge arrestors limit the voltage across protected equipment to a tolerable range, preventing damage to electrical equipment in the circuit. Subsequently, the lightning arrestor returns to a high impedance state. The voltage-current characteristics of surge arrestors indicate that they function as insulators during normal voltage conditions, allowing only a minimal current flow of few a microamps through them. To limit this surge voltage, gapless zinc oxide surge arrestors, commonly referred to as MOSA, are mostly used in power system protection. The voltage-current nonlinear characteristics of these types of arrestors are highly efficient and have supplanted other types of surge arrestors in the system. During normal operation, surge arrestors operate within a steady state region where very low current passes through the surge arrestor, hence this region is also referred to as the low current region. In the second operating region, a small increase in voltage leads to a significant increase in leakage current, thus this region is termed the flat region. The temporary over voltage (V_{TOV}) occurs in this region. In third region, very high current passes through surge arrestor due to discharges of lightning current, and hence this region is called the high current region. However, during overvoltage or surge events, it acts as conductor, allowing large current flows to flow when surge voltage appears at the terminals of surge arrestors.

Plain Rod Gaps

Metallic rod gaps are used in parallel with apparatus to act as discharge devices. Arcing horns are connected across the transformer bushing on each phase. Similarly, such rod gaps are connected across the insulator strings of the transmission lines. The gaps between the two rods are set critically such that under normal conditions, they will not conduct. When, overvoltage appears on the transformer terminal, air between the rods becomes ionized, and flashover occurs between rods. As a result, the surge voltage caused on the system is bypassed through the rod gaps. However, the volt-time (VT) characteristics of rod gaps show that it takes more time to operate than the lightning arrestor [6]. Hence, rod gaps are not fundamentally good protective devices. They are used as back-up protection against overvoltages that occur in the system. Additionally, during overvoltage phenomena, if flashover occurs, it creates a chopped wave across the transformer, which is more sever for the transformer winding. A major drawback of rod gaps is that they are affected by atmospheric conditions, and therefore, the gaps between the rods need to be adjusted based on atmospheric conditions. A typical arrangement of rod gaps is shown in Fig. 2.

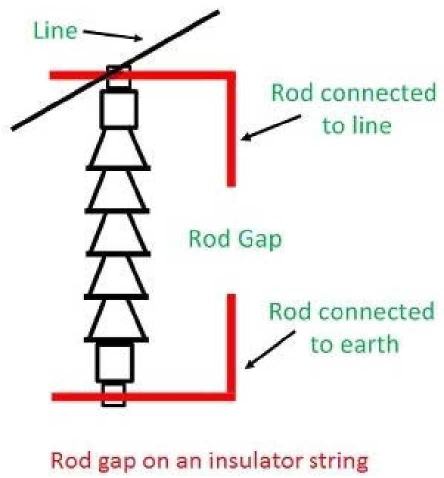

Fig. 2 Surge protection with rod gaps

V. Impact of Arrestor Lead Length on Protective

Protective devices such as surge arrestors or rod gaps are most effective when mounted directly on or adjacent to the transformer. The lead length of the connection must be as small as possible. The inductance of the lead wire, normally used to connect distribution arrestors between line and ground, can be assumed to be 1.3123 μH/m [3]. The voltage build up on the arrestor lead is given by:

$$E = L \frac{di}{dt}$$

where, E is the voltage build up on arrestor in kV, L is the inductance of the arrestor lead in Mh, and di/dt is the rate of rise of surge current.

When the lead of surge arrestor is in its coiled form, it increases its inductance, resulting in a significant increase in the voltage build up on the arrestor. The calculated build up voltage build up across the lead should be added to the arrestor residual voltage when calculating voltages incident to the protected transformer. Surge arrestor residual voltages are generally based on a standard 8/20 μs impulse current wave, where 8 μs is the front time and 20 μs is the time to half of the crest. Published lightning data indicate a median of 31.1 kA and 24.3 kA/μs rate of rise for first stroke and a median of 12.3 kA and

39.9 kA/µs rate of rise for subsequent strokes [3]. If a conservative rate of rise value of 10 kA/µs was used for analysis in [7], the effect of lead length on residual voltage of surge arrestor and protection ratio is given in Table II.

From the results given in Table II, it can be seen that the length of the lead used to connect the surge arrestor plays a significant role in fixing the residual voltage of the arrestor. The connection between the transformer and surge arrestor must be kept as small as possible and should be in a straight configuration, avoiding coils to minimize the lead inductance. For distribution transformers, it is preferable that the lead length is less than one meter. A typical connection arrangement between for a distribution transformer and a surge arrestor is shown in Fig. 3.

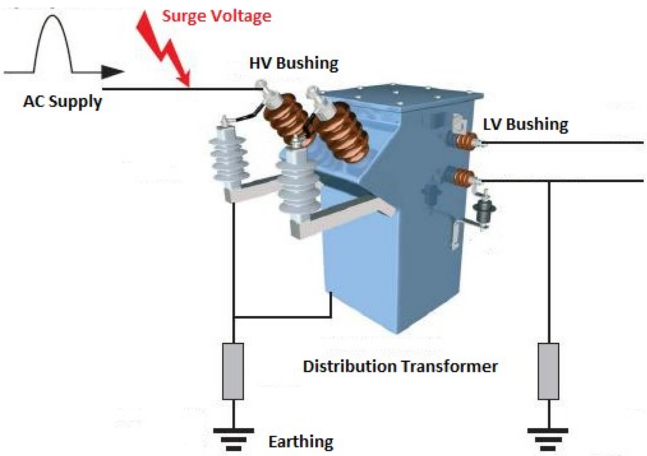

Fig. 3 Connection of surge arrestor

TABLE II
EFFECT OF LEAD LENGTH ON PROTECTIVE RATIO

Parameters	Nominal System Voltage (11 kV)			
	Lead length between transformer terminal and surge arrestor (in meters)			
	1	2	3	3.5
Continuous operating voltage of surge arrestor	9	9	9	9
BIL of transformer	95	95	95	95
$\frac{di}{dt}$ kA/µS	10	10	10	10
Inductance of arrestor lead µH/m	3	3	3	3
Lead wire voltage (E = Ldi/dt)	30	30	30	30
Typical lead length in meter	1	2	3	3.5
Total lead voltage	30	60	90	105
Residual voltage of arrestor (R_V)	22	22	22	22
Total voltage incident at transformer terminal	52	82	112	127
Chopped wave withstand voltage of transformer	105	105	105	105
CWW ratio %	2.01	1.27	0.93	0.82
FWW ratio	1.83	1.16	0.85	0.75
Recommended ratio	1.20	1.20	1.20	1.20

With an increase in the lead length between the surge arrestor and the transformer, the voltage drop across lead is increased, which is then added to the residual voltage of the surge arrestor. Consequently, the residual voltage and the conduction voltage of the surge arrestor increase. This increased residual voltage decreases the protection margin as determined by design calculations.

VI. CONCLUSIONS

For the overvoltage protection of transformers, surge arrestors must be connected across each terminal of the transformer. To minimize the voltage drop during surges, the lead length between the transformer terminal and the surge arrestor must be as short as possible, preferable less than one meter. The connection lead must be in a straight position, not coiled, to minimize inductance. A longer lead length increases inductance, which in turn increases the residual voltage of the surge arrestor and hence reduces the protection margin of the transformer insulation against surge voltages.

ACKNOWLEDGMENT

Authors wish to thank the Management of Electrical Research and Development Association (ERDA), Vadodara for giving permission to present this paper.

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