

Role of Surge Arrester and its Location for Protection of Transformers against Lightning overvoltage

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ABSTRACT: Transformers are essential component of electrical power system. It plays major role in transmission and distribution of electrical power. Transformers installed in the power systems have to withstand overvoltage apart from its continuous operating voltage. This Surge voltage arises in the system either by switching operations of heavy load or by lightning strokes. Surge voltage can cause significant failure of transformer and power system if sufficient protection has not been provided. External rod gaps and surge arresters are connected across transformer bushing for its protection against lightning over voltage. Metal oxide surge arresters (MOSA) are connected across each phase terminal. As per voltage rating of transformer its Basic Insulation Level (BIL) has been defined. Ideally, transformer insulation supposed to withstand over voltage below its BIL. Residual voltage of MOSA is responsible to maintained the voltage level much below the BIL of Transformer. Hence, Voltage rating of MOSA, length of connection lead from transformer bushing terminal as well as its location plays major role for protection during over voltage conditions. At the time of designing transformer insulation, required BIL, MOSA ratings and its operating voltage are considered. However, performance of transformer insulation is largely depends on ratings of surge arrester connected, location of surge arrester, margin considered in insulation design, quantity of surge voltage strike, etc. This paper demonstrate the role of Surge arresters for protection of transformer against lightning over voltage, transformer insulation design, optimum location of surge arresters and effect of its connection lead length, protection margin and methods of protection of transformers against surge voltages have been discussed in detail.

I. INTRODUCTION

Distribution and power transformers installed in the power system are frequently exposed to over voltage caused by lightning strikes. In transmission and distribution system metal oxide surge arresters (MOSA) are widely used for protection against surge voltage. However, lightning strikes are still one of the major cause of transformer failure in the network [1]. Such failures can cause interruption of power supply and makes system unreliable. Consumers always demand for improvement in supply reliability as well as power quality. Hence, system outage required to minimize for reliable power supply. Prime focus need for protection of system components to avoid unwanted failure and outages. MOSA is a device, designed to protect electrical apparatus from transient voltage and to limit the duration and amplitude of follow-current [1]. MOSA connected to in system between phase conductor and earth. When MOSA subjected to an overvoltage from the System to which it is installed, responds by shunting surge current, thereby limiting the overvoltage on the protected equipment [2].

1.1 Origin and Classification of Surge Voltage:

Overvoltage are generally classified with parameters like its duration, wave shape, and according to their effect on the insulation or on the protective device. The voltage stresses within these classes have several origins. They are temporary overvoltage (TOV) and switching Impulse overvoltage (SIV). TOV and SIV also known as slow front overvoltage (SFO). Another overvoltage is lightning overvoltage (LIV), also known as fast front overvoltage (FFO) and very fast transient overvoltage (VFTO) [3]. Each of these overvoltage has different impact on insulation system.

A) TOV can originate from system faults, switching operations of light load such as load rejection, resonance conditions, ferro-resonance etc.

B) The SIV can originate from system faults, switching operations of heavy load (Line energization for long or medium transmission line) etc.

C) LIV originates by natural lightning strikes, on transmission line shield wire or phase conductor i.e. direct or indirect lightning strokes.

D) The VFTO can originate from faults, external flashover across insulators or bushings.

Relationship between p.u. voltage and duration for different kinds of over voltages is shown in Fig.1 [3].

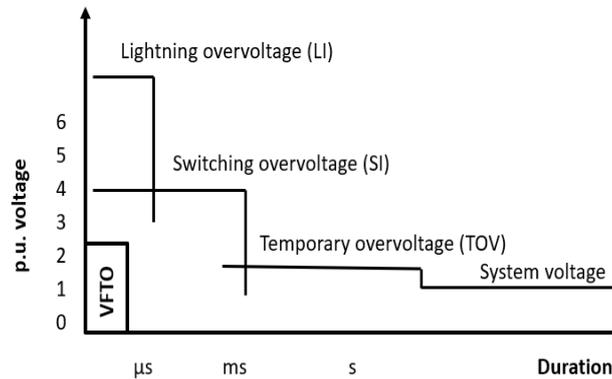


Figure 1: Magnitude and duration of Surge Voltages

The basic insulation level (BIL) of the transformer must be capable to withstand above all types surge voltage at least up to the response time of protective device. In this paper the requirement of insulation level of transformer to withstand the surge voltage, role of surge protective device, insulation coordination of for transformer is discussed in detail. In this paper role of Surge arresters for protection of transformer against lightning over voltage, transformer insulation design, optimum location of surge arresters and effect of its connection lead length, protection margin and various methods of protection of transformers against surge voltages have been discussed in detail.

II. DESIGN CRITERIA FOR INSULATION LEVEL OF TRANSFORMER

BIL of transformer is defined as one minute withstand voltage & peak voltage of a 1.2/50μs wave which does not cause its insulation to fail. Wave shape of 1.2/50μs indicates a surge which reaches its peak value within 1.2 μs and decays to 50 % of the peak value within 50μs. Transformer rated above 220 kV voltage or in case of Applicable, switching impulse voltage is also defined as BIL along with LI voltage. Main insulation (i.e. between HV & LV winding, HV&LV Winding to Earth) & Inter-turn insulation of HV & LV winding, is designed based on the rated voltage and required basic insulation level (BIL). Protective Level of a Surge Arrester is defined based on theory of Insulation coordination [4]. The degree of coordination is measured by the protective ratio (PR) which is represented as,

$$\text{Protective ratio} = \frac{\text{Insulation withstand level}}{\text{Voltage at protected equipment}} \quad (1)$$

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. As the steepness of surge current increases, the arrester presents higher residual voltage thus reducing the protective margin which endangers the life of the transformer [1]. Hence, while designing the BIL of transformer insulation all above basic principle 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 decide required minimum basic insulation level is defined below,

- System analysis consisting of Continuous power frequency voltage.
- Over Voltage, its origin and classification of stressing voltage, Protective level of over voltage limiting device.
- Determination of the co-ordination withstand voltage, Insulation characteristics, performance criteria
- Coordination withstand voltage (Ucw) for Continuous operating voltage the value of the withstand voltage of the insulation configuration in actual service conditions, that meets the performance criterion.
- Altitude correction factor (Ka), atmospheric correction factor (Kt), Transformer test assembly, Quality of Insulation etc.
- Required Withstand voltage (Urw)– (test voltage that the insulation must withstand in a standard withstand voltage test)
- Selection of rated withstand voltage (Uw) i.e. value of the test voltage, applied in a standard withstand voltage test that proves that the provided insulation in transformer complies with one or more required withstand voltages.

The standard rated withstand voltage is given in table no. 1. [5]

Highest system voltage (Um) kVrms	Standard rated power-frequency withstand voltage kVrms	Standard rated lightning impulse withstand voltage
3.6	10	40
12	28	75/95
36	70	170
72.5	140	325
145	230/275	550/650
245	460	950/1050

Table 1: Basic Insulation level of Transformer

III. PROTECTION OF TRANSFORMER AGAINST SURGE VOLTAGE:

The main challenges in protection of transformer against surge voltage following major factors required to be considered,

- a. Nature & magnitude of system overvoltage
- b. Lightning impulse withstand strength required
- c. Voltage characteristics of protective device
- d. Magnitude of overvoltage which may reach to the transformer terminal.

Ideally, overvoltage cannot be predicted accurately as to 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 largely depends on the rate of rise of lightning surge voltage, its magnitude and duration [6]. Further transformer may be subjected to overvoltage several times within one second or so a result of a multiple or repetitive lightning stroke depends on conditions. Hence, design of transformer insulation, protection against over voltage to avoid the failure is challenging task. Various methods are adopted by the system designer for overvoltage protection of transformers.

IV. METHODS OF PROTECTION OF TRANSFORMERS AGAINST SURGE VOLTAGE

The transformers installed in the power system are subjected to over voltage in addition to its continuous rated voltage. The capability of insulation system provided in transformers against surge voltage is verified by performing Impulse test in laboratory. The surge voltage generated at the transformer terminal in an actual system is superimposed over the ac operating voltage to form a waveform that differs from the LI voltage waveform [7]. In the power system protection to the transformer against surge voltage must be provided to avoid the unwanted failure. There are various methods employed by the utilities for the same.

4.1 INTERCEPTION OF DIRECT STROKES

With sufficient knowledge of characteristics of natural lightning and power system 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 rare cases. By providing shield wire or shielding of transmission lines or substations such protection is achieved. The popular method of intercepting lightning stroke is by means of ground wire. The ground wire is placed above the transformer to be protected. The grounding resistance of the wire must be kept as low as possible so that the potential of the ground wire or the supporting structure does not become high enough to cause back flashover from structure to phase conductor. The ground wire is placed over the substation or over the transmission line or at both places.

4.2 SURGE ARRESTERS:

Surge arrester is mostly used for the protection of transformer against surge voltages. Voltage-Current characteristics which indicates that the surge arresters act as insulator during normal voltage hence few micro amp current flows through it. When lightning overvoltage appears in electrical circuit, they rapidly change to low resistance and discharge instantaneous energy to earth. Finally, the surge arrester return to a high impedance state. Thus, Surge Arrester limits the voltage across protected equipment to tolerable range and avoids damage of electrical equipment in the circuit. To limit this surge voltage, now a days Gapless Zinc Oxide Surge Arresters are mostly used in the power system protection which popularly known as metal oxide surge arrester (MOSA). During normal operation surge arresters operates as steady state region and very low current

passed through surge arrester. However, during over voltage or surge it acts as conductor hence, large current flows when surge voltage appears at terminal of surge arresters.

4.3 PLAIN ROD GAPS:

Rod gaps or arcing horns are used in parallel with apparatus which acts as discharge devices. Arcing horns are connected across the Transformer bushing on each phase. Also, such rod gaps are connected across the insulator strings of the transmission lines. Gaps between the two rods are set critically such that in normal condition, it will not conduct. When, over voltage appear on the transformer terminal, air between the rods gets ionized and flashover occurs between rods. Thus, surge voltage caused on the system bypassed through rod gaps. However, Volt-time (V-T) characteristics of rod gaps shows that it takes more time to operate than the Lightning arrester [5]. Hence, rod gaps are fundamentally not good protective device hence, it is used as back-up protection against over voltages occurs in system. Major drawback of the rod gap is, it affects by the atmospheric condition and hence, gaps between the rods required to be adjusted at based on the atmospheric condition.

V. IMPACT OF ARRESTER LEAD LENGTH ON PROTECTIVE :

Surge arresters or Rod gaps will be most effective when mounted directly on or adjacent to the transformer. The critical aspect in selection and application of surge arrestors is the arrester lead length. In case of lightning strikes, the discharge current causes a residual voltage across the terminal of MOSA. Similarly, it also build voltage across surge arrester lead due to its inductance. Voltage build up in an arrester lead will add to the arrester residual voltage. Since a surge arrester is connected in parallel with the protected equipment, the total arrester residual voltage will appear across the protected equipment. Hence, neglecting the impact of lead lengths effects the protective margins of surge arrestors during their selection. This leads to inadequate protection of distribution transformers and other line equipment when the surge arresters are actually installed and may cause failure of transformer. Inductance of the lead wire normally used to connect distribution arresters between line and ground can be assumed to be 1.3123μH/m [8]. The voltage build up on the arrester lead is given by,

$$E = L \frac{di}{dt} \quad (2)$$

Where, E = Voltage build up on arrester in kV
 L = inductance of the arrester lead in mH and
 di/dt = rate of rise of surge current.

When, lead of surge arrester is in coiled form it increases its inductance. This significantly increase in the voltage build up on the arrester. The calculated voltage build up across the lead should be added to the arrester residual voltage when calculating voltages incident to the protected transformer. Surge arrester residual voltages are generally based on 8 μs front time and 20μs time to half of the crest i.e. 8/20μs impulse current wave [4]. Published lightning data indicates median of 31.1 kA and 24.3 kA/μs rate of rise for first stroke and median of 12.3 kA and 39.9 kA/μs rate of rise for subsequent strokes [9]. Conservative rate of rise value of 20 kA/μs has been used for 11 kV & 33 kV system for analysis in this paper. Residual voltage for 9 kV and 30 kV surge arrester has been considered as 25. 7 kV and 97.1 kV respectively [10]. Effect of lead length on residual voltage of surge arrester and protection ration is given in table 2 for 11 kV system and in table 3 for 36 kV system.

Parameters	Nominal System Voltage (12 kV)			
	Lead Length between Transformer terminal and Surge Arrester (in meter)			
	1	1.5	2	3
Continuous Operating voltage of Surge Arrester	9	9	9	9
BIL of Transformer	95	95	95	95
$\frac{di}{dt}$ kA/μS	20	20	20	20
Inductance of arrester lead μH/m	1.312	1.312	1.312	1.312
Lead Wire Voltage (E=Ldi/dt)	26.24	26.24	26.24	26.24

Typical lead length in meter	1	1.5	2	3
Total lead voltage	26.24	39.36	52.48	78.72
Residual voltage of arrester (RV)	25.7	25.7	25.7	25.7
Length of ground lead	0.5	0.75	1	1.5
Ground lead voltage	10	15	20	30
Total Voltage incident at Transformer terminal	61.94	80.06	98.18	134.42
Chopped wave withstand voltage of Transformer	104.5	104.5	104.5	104.5
CWW Ration %	1.69	1.31	1.06	0.78
FWW Ratio	1.53	1.19	0.97	0.71
Recommended ratio	1.20	1.20	1.20	1.20

Table 2: Effect of lead length on protective ratio

Parameters	Nominal System Voltage (36 kV)			
	Lead Length between Transformer terminal and Surge Arrester (in meter)			
	1	1.5	2	3
Continuous Operating voltage of Surge Arrester	30	30	30	30
BIL of Transformer	170	170	170	170
$\frac{di}{dt}$ kA/ μ S	20	20	20	20
Inductance of arrester lead μ H/m	1.312	1.312	1.312	1.312
Lead Wire Voltage (E=Ldi/dt)	26.24	26.24	26.24	26.24
Typical lead length in meter	1	1.5	2	3
Total lead voltage	26.24	39.36	52.48	78.72
Residual voltage of arrester (RV)	90	90	90	90
Length of ground lead	0.5	0.75	1	1.5
Ground lead voltage	10	15	20	30
Total Voltage incident at Transformer terminal	126.24	144.36	162.48	198.72
Chopped wave withstand voltage of Transformer	187	187	187	187
CWW Ration %	1.48	1.30	1.15	0.94
FWW Ratio	1.35	1.18	1.05	0.86
Recommended ratio	1.20	1.20	1.20	1.20

Table 3: Effect of lead length on protective ratio

From the results given in table 2 and table 3 it can be seen that the lead length used for the connection of the surge arrester plays major role to decide the residual voltage of arrester. Connection between transformer

terminals to surge arrester must be as small as possible. Similarly, the length of ground lead i.e. connection between surge arrester earth terminal to earthing must be as low as possible. The connection lead should be straight not in coil shape to minimize the lead inductance. It is preferable that the lead length must be less than one meter in case of distribution transformers. Typical connection arrangement between for distribution transformer and surge arrester is shown in figure 2 and figure 3. .

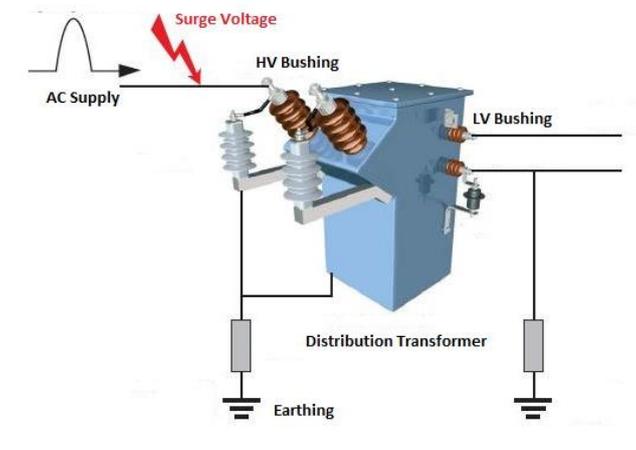


Figure 2: Connection of Surge Arrester



Figure 3: Connection of Surge Arrester

With increased in lead length between surge arrester and transformer, the voltage drop across lead is increased, which is added in residual voltage of Surge arrester. Hence, residual voltage and conduction voltage of surge arrester increase. Increased residual voltage decrease the protection margin decided as per design calculation. For 12 kV system if the length of connecting lead and grounding lead up to 1.5 meter, meets the requirement of protection margin of 1.2. Similarly, for 36 kV protection margined if the length of connecting lead and grounding lead up to 1.5 meter, meets the requirement of protection margin of 1.2. Above that in both the cases, system does not meets the requirement of minimum protection margin of 1.2.

VI. CONCLUSIONS

For surge protection of transformers, surge arrester must be connected across each phase of the transformer. Lead length between transformer terminal and surge arrester must be as low as possible preferable below one meter. The location of surge arrester must be as near as possible. The earth connection lead from arrester earth terminal to earthing point must be less than 1 meter length. Connecting lead must be in straight position not in coiled form to minimize the inductance. Higher lead length increase inductance which increase voltage across lead. Increased lead voltage will increase residual voltage of surge arrester. This reduce the protection margin of transformers insulation against surge voltages, may leads to failure of transformer during surges.

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