Lightning protection of pole-mounted transformers and its applications in Sri Lanka

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ABSTRACT

This paper presents measures for better lightning protection of pole-mounted distribution transformers of Medium Voltage (MV) systems. One intention is to provide a general bench mark for lightning protection, of pole-mounted transformers, to ensure proper installation and to reduce the high lightning failure rate of pole mounted distribution transformers existing in Sri Lanka.

The High Voltage side of transformers is usually protected against lightning by surge arresters. In installation of HV surge arresters, the separation length between the arrester and the high voltage bushing is of paramount importance. Thus the calculation of the separation lengths and failure rates are first discussed and the drawbacks of the present method of installation are presented. The required separation depends on the tower configuration. viz. tower earthing, system voltage (or tower insulation), tower surge impedance, collection area etc. and the length of the earth wire of the arrester. Ground flash density is also an important parameter in determining the separation length and failure rate.

Selection of arresters with proper residual voltage imparts a considerable contribution to the transformer protection. An alternative approach for this is also presented.

The role of the earth resistance and its contribution to High Voltage and Low Voltage failures due to lightning are discussed, indicating typical modes of failure. The determination of a safe value for the earth resistance is also presented

Finally, the paper presents simplified preventive measures that can be implemented in the Sri Lankan context.

LIST OF SYMBOLS

- β : Reflection coefficient at transformer
- b: Horizontal span between outermost conductors (m)
- BIL: Basic insulation level (kV)
- E_t: Peak surge voltage at transformer (kV)
- H: Line height above ground (m)
- I_{AM} : Maximum current through the arrester (kA)
- I_o: Lightning stroke current, peak value (kA)
- I_{ox}: Lightning stroke current, peak value, which exceeds slope S_A at A, at a distance x away from A (kA)
- k : corona-damping constant (µs/kVm).
- l: Separation between arrester and transformer (m)
- N_g: Number of strokes per km^2 per year
- N_f: Number of lightning surges arriving at A with a slope higher than S_A per year.
- P_{Io}: Probability of lightning current exceeding I_o.
- R_{ai}: Impulse resistance of arrester earth rod. (Ω).
- S_A : (de/dt) rate of rise of surge voltage at receiving end (kV/µs)
- S_f: Shielding factor due to nearby objects
- S_o: (de/dt) rate of rise at point of strike (kV/µs)
- t_f : Wave front time (µs)
- t_s: Duration between two lightning surges which cause damage to the transformer (years)
- U_l : Line insulation level (kV)
- U_p: Arrester residual voltage (kV)
- v: Velocity of wave propagation (m/µs)
- V_{Ra}: Voltage across earth resistance of arrester earth rod. (kV)
- X: Distance in which a surge with an infinite slope will decay to slope S_A at A (m)
- Z: Surge impedance of line (Ω)

1.0 INTRODUCTION

Electrical power is indispensable for present day living. The reliability of a power system is therefore of utmost importance in any sphere of activity. The reliability of a distribution system is highly dependent on the reliability of transformer protection. It is known that lightning is the single most important cause of failure in Medium Voltage (below 72.5kV) lines of distribution systems [1]. The commonest cause of transformer outages or rather failures is lightning strikes to or nearby distribution lines.

Although high voltage transmission lines are protected by shield wires, this has no practical meaning in the case of MV lines, since the tower earthing and the insulation strength cannot economically be improved to such a degree that back flashovers are avoided [2].

The lightning protection of MV networks is difficult because of the relatively low insulation levels of such lines compared with the voltages, which can be developed by lightning surges.

Failure analyses of transformers done by different utilities worldwide have revealed that the failure rate may go as high as 4.5% - 5% per year [3, 4,5].

Several causes, such as lack of proper analysis techniques, selection and installation of protection systems, contribute to such failure rates.

The arrester earth resistance is, most of the time, thought to be less important, yet imparts a considerable contribution in transformer failures in systems with two separate earth electrodes for the tank and the low voltage (LV) neutral.

Given all the above facts it is evident that many of the failures may have been avoided by proper analysis of the transient behaviour of transformers and their protection equipment.

2.0 OVERVOLTAGES IN PRESENCE OF LIGHTNING SURGES.

Figure 1 shows the surge arrester protection of a transformer connected to an overhead line.

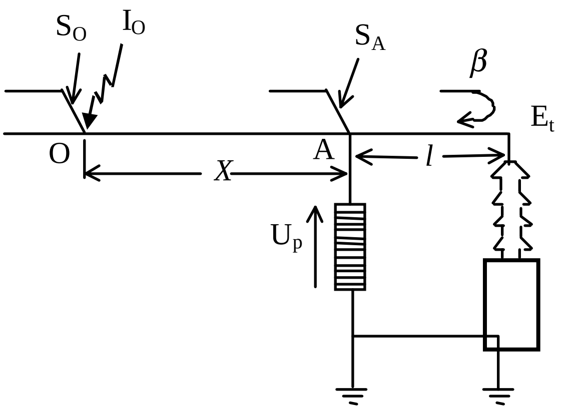

Figure 1 - Surge arrester protection of a transformer

For the line segment OA in figure 1, the induced over voltage at O for a lightning current of magnitude I_o is given by

$$E_0 = \left(\frac{I_0}{2}\right).Z$$

and the slope of the induced surge for a linearly rising wave is given by

$$S_0 = \left(\frac{I_0}{2}\right).\left(\frac{Z}{t_f}\right) \qquad (1)$$

It has been shown in [6] that the slope of the wave reduces as it travels along the line. The impinging surge at A thus has a slope given by

$$S_A = \frac{1}{\left(\frac{1}{S_0} + kX\right)} \qquad (2)$$

Where k = 1.5 *10^{-6} µs/kVm

Using normal reflection theory [7 - Chap 10] gives the peak voltage at the transformer terminal as

$$E_t = U_p + \beta S_A\left(\frac{2l}{v}\right) \text{ kV}$$

In practice, the transformer surge impedance is very much greater than that of the line. Therefore, in general, it can be assumed that the reflection coefficient β = 1.

With this assumption,

$$E_t = U_p + S_A\left(\frac{2l}{v}\right) \qquad (3)$$

This expression is valid for S_A 2*l/v < Up.

For the worst case where S_A*2*l/v ≥ Up, the transformer peak voltage is given as

$$E_t = 2U_p \qquad (4)$$

2.1 Protection Against Direct Strokes

Direct strokes to a line is one of the key factors in the selection of lightning protection for a distribution system. The number of direct strokes to a distribution line depends on several factors such as line height, horizontal span between outermost phase conductors, shielding factor and the ground flash density. The number of direct strokes can reasonably be computed from following equation [1,8].

$$N = N_g\,(b+28H^{0.6})(1 - S_f)10^{-6} \text{ strokes/km year} \qquad (5)$$

For an arrangement, such as in figure 2, [8] gives the shielding factor, S_f, due to near by objects to vary from 0.3 to as high as 0.5. With h=H and x=H a reasonable value for the Sri Lankan system is 0.5.

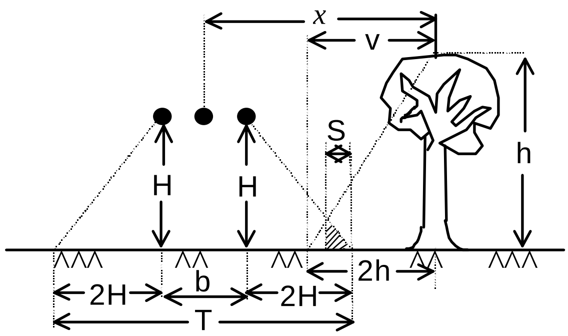

Figure 2 - Shielding due to nearby object

Although nowadays most of the transformers are protected with surge arresters, they still record very high failure rates. Most of the failures seem to be due to the excessive separation lengths between the transformers and the surge arresters.

2.1.1 Protection Method One

There is no well-established method to assess the performance of a lightning protection system quantitatively.

However one method has proposed [6] that the arrester location is determined in order to ensure a failure rate below a certain value during lifetime of a transformer.

If a transformer with a lifetime of LF years is considered and the acceptable failure rate during the lifetime is FR%. Then, to achieve a failure rate below FR%, the transformer should be protected against a lightning that will occur only once in t_s years, where t_s equals (LF/FR)*100..

The number of strokes received by line segment OA of figure1 during t_s can be calculated as
$t_s = N\ t_s\ X$

To avoid any failure, the transformer should thus be protected against lightning strokes, which are equal or less severe than that can occur only once in every $N.t_s.X$ strokes. Probability (P_{Io}) of getting one lightning stroke out of $N.t_s.X$ strokes is equal to $(1/N.t_s.X)*100\%$. Thus, the transformer should be protected against a lightning surge (I_o) which has a probability P_{Io} to exceed value I_o.

The following example illustrates the determination of the arrester separation as per above method.

Example

A 33 kV, 3 wire distribution line, with a thunder level of 80 days at its location, has H = 9.2 m, b = 2.7 m, S_f = 0.5 and Z = 450 Ω. The transformer BIL is 200 kV and the arrester U_p is 110 kV. The required FR is 5% and LF is 20 years. The velocity of wave propagation is taken as 300 m/µs

It is given in [6] that the appropriate span length to use is 300m (distance OA of figure 1) in MV systems.

Thunder days per year	Flashes per km^2 (Ng)
5	0.2
10	0.5
20	1.1
30	1.9
40	2.8
50	3.7
60	4.7
80	6.9
100	9.2

Reproduced from BS 6651

Table 1 - Relationship between Isokeraunik level and lightning flashes per km^2 per year

Since the Isokeraunik level is given as 80, the ground flash density can be obtained from Table 1 [9].

By substituting in equation (5), total number of lightning strokes in 300m line segment can be calculated as

$6.9(2.7+28x9.2^{0.6})(1-0.5)10^{-6}x300$
= 0.113 stroke per year

Allowed time span between two damaging strokes
t_s = 20/0.05 = 400 years
Therefore, the probability (P_{Io}) of the lightning current (I_o) for which protection is required is given by

$P_{Io} = 1/(0.113*\ 400) = 0.022$

As shown in figure 3, from information available in [7] and [8], the probability (P_{Io}) of lightning current to exceed the same value can reasonably be calculated from equation (6).

$$P_{Io} = e^{-0.02878Io} \qquad (6)$$

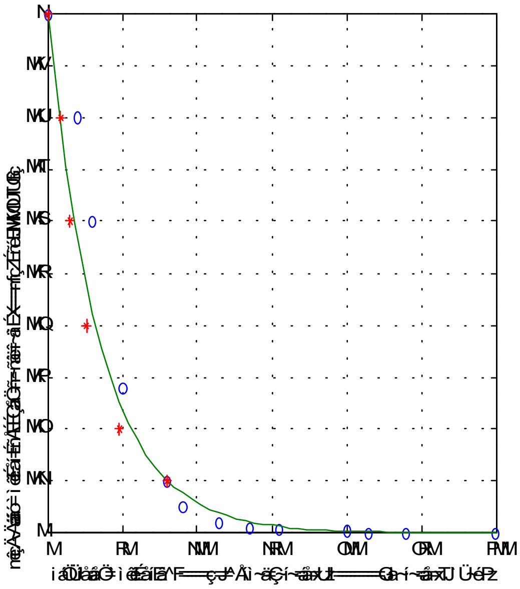

Figure 3 - Probability of current being exceeded

It can thus be calculated that the value of I_o, with a probability of 0.022 to exceed I_o, is 135kA.

According to [7-Chap 3] and [8], a reasonable value to be assumed for the wave front time (t_f) is 5µs.

For I_o of 135 kA which hits the line 300m away from A, from equation (2) S_A can be calculated as

$$S_A = \frac{1}{\left(\frac{1}{\frac{135}{2}\times\frac{450}{5}} + 1.5\times 10^{-6}\times 300\right)} = 1627 \quad kv/\ \mu s$$

With a safety margin of 20% at the transformer, the equation (3) can be rearranged to obtain separation between arrester and transformer as given by following equation

$$l = \frac{(0.8E_t - U_p)v}{2S_A} \qquad (7)$$

Substitution of values gives the separation as

$l = (0.8*200-110)*300/(2*1627) = 4.6m$

Assuming that the lightning protection is designed marginally for S_A, this protection scheme will be effective for any stroke of value below I_o originating before O. If the same lightning I_o (135 kA) hits the line after O then the protection will be ineffective since the impinging S_A will be greater than that is designed for.

Thus, even lower values of lightning currents hitting the line between O and A can cause higher values of S_A than that for which the protection is designed. Therefore the failure rate would be much more than the designed FR%.

2.1.2 Proposed Improved Protection Method

Having examined the drawbacks of the existing scheme, an improved and more accurate method has been formulated and presented in this section.

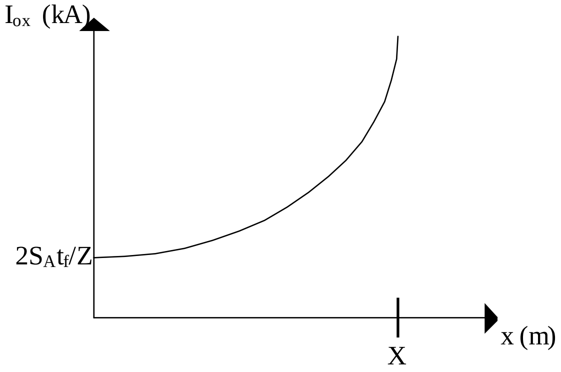

Fig 4 - Variation of I_{ox} with x

Let I_{ox} be the lightning current which causes the slope of incoming wave to be higher than S_A after hitting the line at a distance x away from A. By substituting (1) in (2), with X being x, the value of Iox which causes expected S_A at A can be calculated as in equation (8).

$$I_{ox} = \frac{2\, t_f S_A}{(1 - S_A kx)Z} \qquad (8)$$

Therefore, any current hitting the line at x exceeding value I_{ox} will cause de/dt to be higher than S_A at A. Figure 4 shows the variation of I_{ox} with distance x from A. X is the farthest point away from which distance an infinite surge would decay to cause acceptable S_A once received at A.

For an infinite value I_{ox}, from equation (8), the value of X can be calculated as

$$X = \frac{1}{S_A k}$$

For almost all practical cases, it is appropriate to select 300kA as the maximum of I_{ox} since it has only a 0.0002 probability of being exceeded.

Thus a fairly accurate approximation is given by

$$X = \left(1 - \frac{2t_f S_A}{300Z}\right)\left(\frac{1}{S_A k}\right) \qquad (9)$$

For the above considered example
$X = (1-2*5*1627/(300*450))/(1627*1.5*10^{-6})$
$= 360$ m
Thus the X calculated as per equation (9) is 360m only.

Considering a line segment Δx of line OA of figure 1, from equation (5), the number of strokes per year in Δx can be calculated as

$$\Delta N = Ng\,(b+28H^{0.6})(1 - Sf)\, 10^{-6}\Delta x$$

Then, the number of strokes per year on Δx which causes a higher de/dt than S_A at A is

$$\Delta N_f = P_{Iox} * Ng\,(b+28H^{0.6})(1 - Sf)\, 10^{-6}\Delta x$$

P_{Iox} is the probability of lightning current exceeding I_{ox}. P_{Iox} can be calculated from equation (6) by substituting I_o with I_{ox}. I_{ox} is then substituted with equation (8). X is calculated from equation (9) for the given conditions. By integrating over X, the total number of surges received at A per year with de/dt exceeding value S_A can be calculated from

$$Nf = N\int_0^X e^{-i(x)}dx \text{ strokes per year} \quad (10)$$

where $i(x) = 0.02878\left(\frac{2*t_f}{Z}\right)\left(\frac{S_A}{1-S_A kx}\right)$

$N = N_g\,(b+28H^{0.6})(1-S_f)10^{-6}$

For the example considered earlier, for S_A of 1627kV/µs and X equals 360m, equation (10) gives

N_f = 0.0581strokes per year

Therefore, total number of damaging surges in lifetime (LF) = N_f*LF = 1.162. Thus, transformer will receive 1.162 surges exceeding value S_A during LF and consequently transformer will certainly fail before the end of LF.

Average time between two surges causing higher slopes than S_A (t_s) is given by $1/N_f$. Failure rate (FR) is calculated as (LF/ t_s)*100%.

Thus,

$$(FR) = LF * N_f * 100\% \qquad (11)$$

Therefore, FR for the example is 116.2%. Transformer protected for 5% failure rate by method one will have an actual failure rate well above 100%.

2.1.2.1 Application

Starting with a suitable value for S_A, by trial an error, (9) and (10) can be solved to calculate S_A until required N_f is obtained. Next, separation length *l* can be calculated from equation (7).

For previous example, from equation (11) the acceptable value of N_f was calculated as
N_f = 0.05/20 = 0.0025.

Starting with S_A equals 1627 kV/µs, which was, calculated for method one, by trial an error, (9) and (10) can be solved to calculate S_A until required N_f is obtained. It was found that S_A is 3300 kV/µs for N_f of 0.0025. By substituting S_A in equation (7), separation length is calculated as, *l* = 2.3m.

For proper protection separation length will have to be reduced to 2.3m from 4.6m in method one. Therefore it is evident that separation length of arrester should be as small as possible.

Even small increases of around 1m to 2m would drastically affect the reliability of the transformer. Calculation of this length should be done considering all the factors presented in this section. Arrester itself will be of around 1m long. Therefore, all the other connections will have to be terminated in 1m to 1.3m length and most preferred solution is to fix the surge arresters right top on of the cover plate of the transformer.

2.2 Protection with Arresters Having Low Residual Voltages.

Most of the transformers are protected with surge arresters. The residual voltage of the arrester plays a very important role in protecting the transformers.

By selecting arresters with residual voltages as low as possible, a far better protection can be achieved. This can be implemented very easily for effectively earthed systems since they can be protected with arresters having low operating voltages.

For the general case with β =1, it can be shown that if **Up $\leq$ (acceptable BIL)/2**, E_t will not exceed the acceptable BIL at the transformer independent of the lead length. By this means 100% protection can be achieved.

Consider again the previous example.

Required Up $\leq$ 0.8 *BIL/2 = 80kV.

This is not a commercially available value. However, supplier B of appendix 1 has an arrester with a residual voltage of 89kV at 10kA. This can be used in an effectively earthed 33kV system.

Safety margin = (BIL - 2*Up)/BIL = 11%

$$I_{AM} = \frac{(2*U_l - Up)}{Z} \qquad (12)$$

Protection with this arrester will give a 100% protection with a 11% safety margin regardless of the separation length. Since the level of protection is very high, 11% margin is acceptable.

As given in [6,7-Chap 10] it can be shown that the maximum current through the arrester is given by (12).

The margin of protection can be further increased by grounding the cross arms of at least last three poles. It is given in [2] that insulation level of a line (U_l) with grounded cross arms is limited to a maximum of 900kV. Therefore,
Current through arrester = (2*900-89)/450 = 3.8kA

Since the current is limited to a small value of less than 4kA, the residual voltage will be smaller than Up. This will further increase the safety margin. This mode of protection can be very effectively done for MV systems.

Moreover, as given in [6, 8-Chapter 10] typical line insulation level for a 33kV system similar to that of example considered and is limited to around 660kV with cross arms which are being earthed. Therefore it can be shown from equation (12) that the arrester current for the example will actually be limited to 2.7kA. This reassures that if cross arms are earthed, the tendency to exceed rated Up is very much less unless the lightning hits the line very close to the transformer.

Alternatively, it is possible to increase the BIL of transformer itself. In this example a 9% further increase of transformer BIL is required for 20% protection margin. This can be achieved at a 2% increase of the cost.

2.3 Effect of Earth Resistance of Earth Electrodes

All transformer installations are earthed using two separate electrodes. Earth resistance of these electrodes play a significant role in the lightning protection of transformers.

Transformers are having one common earth electrode for the tank earthing and surge arrester earthing and one separate electrode for Low Voltage neutral earthing. Most of the time, the earth resistance of these electrodes are neglected. However higher the earth resistance of arrester earth rod higher will be the tendency for failures.

When surge currents are passing through earth electrodes, their earth resistance will be reduced below the normal values obtained by earth megger testing due to excessive ionisation of the soil. The amount of reduction depends on several factor such as earth resistivity, number of earth rods in parallel, their shapes and geometry and lightning current. More information can be found in [10].

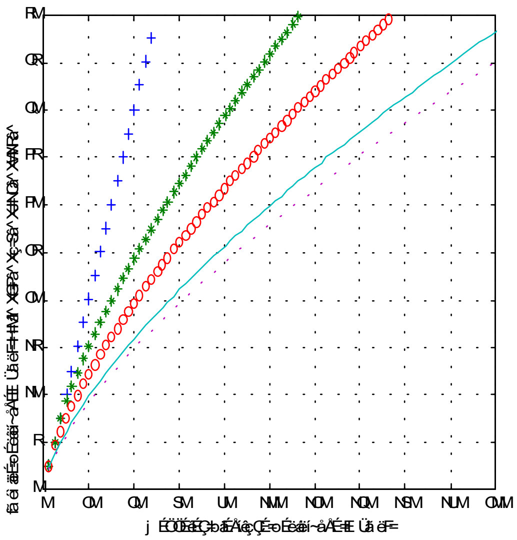

Figure 5 - Impulse Earth Resistance Vs Normal Earth resistance for single rod

Figure 5 and figure 6 show an analysis of variation of earth resistance under impulse currents for 2m long earth rods of 20mm diameter using the derivations given in [10]. Figure 5 is for single rod arrangement and figure 6 is for two parallel rods with a separation of 2m.
For a MV line with no cross arm earthing, maximum line insulation level will be around 2700kV to 3000kV[2,6].

For an MV line as in previous example with surge impedance of 450Ω from equation (12) it can be shown that the typical maximum impulse current flowing through a surge arrester is limited to 12kA to 14kA without earthed cross arms and 4kA with earthed cross arms.

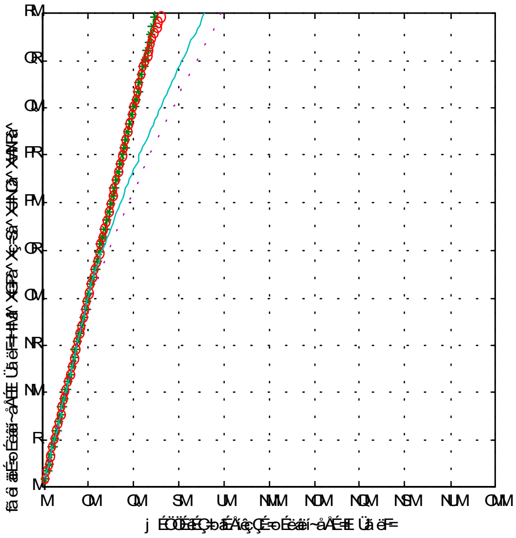

Figure 6 - Impulse Earth Resistance Vs Normal Earth resistance for two rods in parallel.

For currents in above range, from figures 5 and 6 it is obvious that the reduction in earth resistance under impulse currents is prominent for single rod only. Therefore, it is important to consider electrode arrangement before deciding any reduction of earth resistance of MV lines.
Figure 7 shows a typical layout of a transformer installation. When an impulse current flows through arrester to the ground a voltage builds up across the resistance of earth rod. This voltage is given by

$V_{Rai} = R_{ai} * I_{AM}$

Since tank is also connected to the same rod, impulse potential of tank with respect to earth (V_{T-E}) is also at V_{Rai} potential. This gives impulse voltage of transformer terminal with respect to earth as

$V_{HV-E} = Up + V_{Ra}$

Low voltage neutral is separately earthed and no lightning impulse is flowing through this. Therefore, impulse voltage of LV winding with respect to earth (V_{LV-E}) is at zero as far as lightning performance is considered.

This gives impulse voltage (V_{H-L}) of HV winding with respect to LV winding as

$$V_{H-L} = V_{HV-E} - V_{LV-E} = Up + R_{ai} * I_{AM} \qquad (13)$$

Moreover, impulse voltage of LV winding with respect to tank (V_{LV-T}) can be calculated as

$$V_{LV-T} = V_{LV-E} - V_{T-E} = R_{ai} * I_{AM} \qquad (14)$$

Since magnetic core is internally connected to the tank, the same V_{LV-T} applies between LV winding and the core.
From these information, it is evident that if either V_{H-L} is greater than BIL of transformer or V_{LV-T} is greater than insulation level of LV then the transformer will fail at the weakest point of insulation

2.4 .1 Application to Previous Example

By equating equation (13) to rated BIL with required safety margin the recommended value of impulse earth resistance can be calculated as

$$R_{ai} = \frac{(0.8BIL - Up)}{I_{AM}} \qquad (15)$$

With earthed cross-arms I_{AM} will be limited to 3.8kA.
R_{ai} = (0.8*200 - 110)/3.8 = 13 ohms

For this, recommended normal earth resistance obtained from figure 5 for single rod is around 20 ohms and that obtained from figure 6 for two rods is 13 ohms.
Without earthed-cross arms I_{AM} will be around 12kA
R_{ai} = (0.8*200 - 110)/12 = 5 ohms

For this, recommended normal earth resistance obtained from figure 5 for single rod is around 10 ohms and that obtained from figure 6 for two rods is 5 ohms.
Also it should be noted that the R_{ai} obtained from equation (15) should be substituted in equation (14) and checked whether V_{LV-T} is below the value that can be withstood by LV winding. Other wise LV winding would fail even though the HV winding is protected.

For this example; V_{LV-T} = 13*3.8 = 50 kV.
It should be checked from the manufacturer whether the insulation between LV winding and tank or magnetic core winding can withstand 50kV.

3. TYPICAL APPLICATION IN SRI LANKAN SYSTEM

Figure 7 shows a typical layout of a transformer installation.

For above arrangement the separation between arrester and transformer is equal to addition of a1, a2, a3, and a4 and it is given as l= a1+a2+a3+a4

For an MV installation with poles of 11m height typical values would be around a1=0, a2=5m, a3= 4m and a4=0.5m. Therefore l = 9.5m. For a transformer installation similar to previous example in all other aspects, equation (7) gives a rated S_A of 789kV/μs.

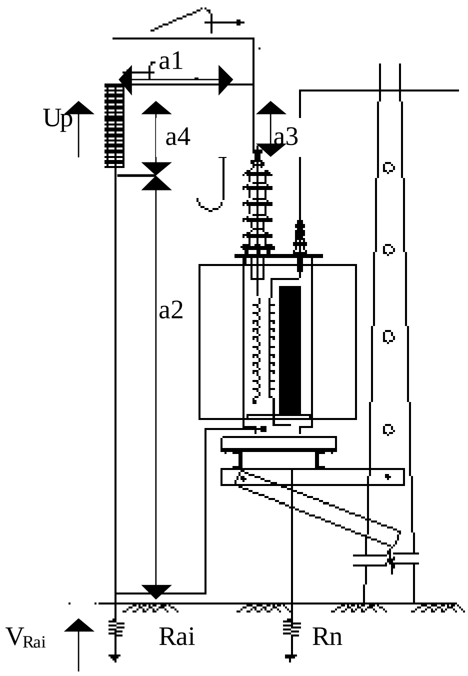

Figure 7- Layout of a Transformer Installation

For practically possible maximum lightning current of 300kA, from equation (9) X can be calculated. Using these values in equation (10), N_f is calculated as 0.103 strokes per year. Therefore, this transformer will receive one destructive stroke in every 9.7 years. Therefore, an average transformer will fail in 9.7 years due to lightning only.

Report on analysis of earth resistance of arrester earth rods prepared by Lanka Transformer limited [11] shows that the average value is around 40 ohms for most parts of the country except for Anuradhapura and Polonnaruwa. For a single earth rod for arrester with line cross arms are earthed, from figure 5, R_{ai} is calculated as 25 ohms. Thus, equation (13) gives an impulse of 178kV between HV and LV this reduces the safety margin to 12%. For two rod case this will increase to 222kV and protection margin becomes minus 9%. If cross arms are not earthed repercussions will be further aggravated.

Since there are many other effects which cause transformer failures, the average life time will be much less than 9.7 years.

Separation length between arrester and transformer can be considerably reduced either by making the common connection of earth wire at the cover plate level or by introducing surge arresters right on top of cover plate. Earth resistance of arrester earth rod should typically be below 20ohms for a lines with earthed cross-arms and below 10 ohms for lines with unearthed cross-arms. Transformer failure rates in real practice will be slightly lower than expected due to the safety margin of 20%.

4. FUTURE WORK

Induced voltages due to near by strokes cause considerable overvoltages frequently in MV lines. Much work has been done on theories of protection of overhead distribution systems against direct strokes. However, the importance of induced strokes has been recognised only recently[12]. Therefore, the effect of line induced surges on transformers performance should be studied.

Insulation failures of high voltage side might have been caused due to surges transferred form low voltage side. Therefore, a proper analysis should be done. Relationship between the failure rate and arrester earth resistance can be studied.

5. CONCLUSION

Based on the information presented in this paper following conclusions can be made.

1. Determination of separation length between surge arrester and transformer should be based on ground flash density, tower configuration, shielding due to other objects, damping due to corona, probability of lightning, expected failure rate of transformers etc. This length should be as smaller as possible for effective surge protection
2. Surge protection of transformers can be very effectively done by selecting surge arresters with residual voltage (at 10kA) less than the half of the acceptable BIL of transformer and by earthing cross arms of the transmission line.
3. Line insulation level or maximum current through surge arrester should be considered in determining earth resistance of arrester earth rod. This should be as small as possible especially when more than one electrode is used or when line cross-arms are not earthed. Reduction of earth resistance due to impulses is not of much importance for arrester earth rods of MV systems.

4. For more accurate results, shielding factor, corona damping constant, line surge impedance, thunder level, line insulation level and impulse resistance of earth rods should be calculated as close as possible to actual figures of the concerned installation

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APPENDIX 1

Supplier A

Guaranteed performance data of Surge Arresters

Rated voltage	Max cont. operating voltage	Maximum residual voltage U_p (peak value) 8/20 us Current wave		
rms value kV	U_c rms value kV	5kA U_p kV	10kA U_p kV	20kA U_p kV
7,5	6	18,6	20,0	22,4
11,3	9	27,9	30,0	33,6
12,5	10	31,0	33,3	37,3
15,0	12	37,2	40,0	44,8
18,8	15	46,5	50,0	56,0
22,5	18	55,8	60,0	67,2
26,3	21	65,1	70,0	78,4
30,0	24	74,4	80,0	89,6
33,8	27	83,7	90,0	101,0
37,5	30	93,0	**100,0**	112,0
41,3	33	102,0	110,0	123,0
45,0	36	112,0	120,0	134,0

Supplier B

Guaranteed performance data of Surge Arresters

Rated voltage	Max cont. operating voltage	Maximum residual voltage U_p (peak value) 8/20 us Current wave		
rms value kV	U_c rms value kV	5kA U_p kV	10kA U_p kV	20kA U_p kV
11,2	9	26,1	27,7	30,6
12,5	10	29,0	30,7	34,0
13,7	11	31,9	33,8	37,4
15,0	12	34,8	36,8	40,8
16,2	13	37,7	39,9	44,2
17,5	14	40,6	43,0	47,6
18,7	15	43,5	46,0	51,0
20,0	16	46,4	49,1	54,4
21,2	17	49,3	52,2	57,8
22,5	18	52,2	55,3	61,2
23,7	19	55,1	58,3	64,6
25,0	20	58,0	61,4	68,0
26,2	21	60,9	64,5	71,4
27,5	22	63,8	67,5	74,8
28,7	23	66,7	70,6	78,2
30,0	24	69,6	73,7	81,6
31,2	25	72,5	76,8	85,0
32,7	26	75,4	79,8	88,4
33,7	27	78,3	82,9	91,8
35,0	28	81,2	86,0	95,2
36,2	29	84,1	**89,0**	98,6
37,5	30	87,0	92,1	102,0
38,7	31	89,9	95,2	105,4
40,0	32	92,8	98,2	108,8
41,2	33	95,7	101,3	112,2