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Simplified Approach to Calculate the Back Flashover Voltage of Shielded H.V. Transmission Line Towers

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***Abstract*—over voltages due to switching or lightning may cause damage for the transmission line insulators, transformers and switchgear. The flow of overvoltage to earth through transmission system towers causes an increase in the potential of metal structure and the earth potential and may create back flashover voltage causing failure to transmission system insulators in which transmission line outages occur. In this paper the effect of tower grounding surge impedance on the back flashover is investigated. The coupling factors between the shielding wires and the healthy conductors are considered.**

***Index Terms*—Back flashover voltage, H.V.T.L., Shielded, Towers**

I. Introduction

For properly designed lines having shield wires, lightning strikes to the lines will terminate on the shield wires and it will be conducted into the ground towers and grounding system. It is possible under certain circumstances due to the high energy of lightning to generate sufficient voltage across insulators to cause them to flashover [1]. The grounding system is never perfect (i.e. zero footing resistance) and the structure itself possesses a surge impedance. The surge current flowing through the tower structure and the footing impedance cause a voltage rise of the structure above ground voltage [2].

The surge voltage appears across a phase insulator may be in many cases sufficiently high to cause a back flashover voltage over the transmission line insulators. The back flashover voltage depends on the coupling factor which is a function of the relative spacing of conductors to ground and conductors to shield wires, the tower structure impedance and ground system impedance [3, 4]. In this paper investigations are carried out to study the back flashover voltages of 500 kV transmission lines. The effect of grounding system surge impedance, the tower structure surge impedance and coupling factor between phases and shielding wires on the back flashover voltages magnitude are studied.

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II. Models of System

A. Lightning Current Impulse

The properties of lightning and switching surges have been well summarized in [5]. Usually, the discharge current increases from zero to a maximum in few µs (from 0.1 to 10 µs), then declines to half the peak value in about 20 to 1000 µs. The typical value of the peak current derivative *di*/*dt* is about 110 kA/µs. The peak value of the stroke current is about 15-30 kA, and some stroke currents could be about 250 kA (probability of occurrence less than 0.1%) [5].The peak current value of 26kA has 50% probability or 75% probability. Also it is found that 14 kA is about 87.5% probability correlation [6-10]. The lightning stroke impulse current source which will be used as an input for the transient analysis of grounding system in the present study equation is [5]:

$$I(t) = I(e^{(-\alpha_1 t)} - e^{(-\alpha_2 t)}) = I(e^{(-7924t)} - e^{(-400109t)}) \quad (1)$$

B. Modeling of ground and tower system for transient studies:

B.1 Grounding System Modeling

The ground rod impedance is represented by a lumped R-L-C circuit Fig. 1 [10]. In Fig. 1 the current impinges on the rod electrode and enters the ground, which in addition to its resistivity has a dielectric constant ε. Thus the ground electrode will have a capacitance, as reciprocal to the resistance and inductance [11, 12].

$$R = \left(\rho/_{(2\pi l)}\right) . ln\left(^{2l}/_{a}\right) \ \ ohm \quad (2)$$

$$C = \left(^{(\varepsilon_r . l)}/_{\left(2ln\left(^{2l}/_{a}\right)\right)}\right) . \left(^{10^{-9}}/_{9}\right) \ \ farad \quad (3)$$

The inductance of such a rod is

$$L = 2l . ln\left(^{2l}/_{a}\right) . 10^{-7} \ \ henry \quad (4)$$

Where *l* is the rod length in meter, a is the radius of the driven rod and ρ is the soil resistivity in Ωm. The capacitance of a driven rod of moderate length plays no significant part even with rapid lightning phenomena. Transient behavior of grounding systems can be calculated using ATP program [13].

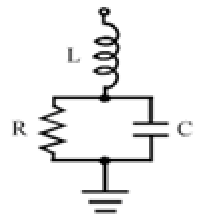

Fig.1. current models of a vertical ground rod

The voltage drop on the electrode inductance L will be:

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

$$= Li[-\alpha_1 1\ e^{(-\alpha_1 1\ t)} + \alpha_1 2\ e^{(-\alpha_1 2\ t)}\ ]$$

(5)

For the tower grounding system having n vertical ground rods the total impedance equals

$$Z_T(t) = \frac{Z(t)}{n} + (n-1)M\frac{di}{dt}$$

(6)

Where Z (t) is the transient impedance of one rod and, n is number of rods, M is the mutual impedance factor between rods. The transient voltage across the grounding system can be obtained by:

$V(t) = Z_T(t).i(t)$

(7)

B.2 Tower Modeling

Tower can be represented as surge impedance. It has inductance and resistance. The voltage across the tower structure can be represented by the equation:

$$V_{tower}(t) = i(t)R_{tower} + L_{tower}\frac{di}{dt}$$

(8)

Where i is the amplitude of the lightning, L_{tower} is the inductance of the tower structure. Its value for current carrying conductors is approximately 1.7 µH/m, di/dt is the average steepness of the front of lightning current (kA/µs) and R_{tower} is the tower structure surge, its value can be calculated according to the formula given by Cigré [14]:

$$R_{tower} = 30\ln\left[\frac{2(h^2 + x^2)}{x^2}\right]$$

(9)

Where h is the tower height and x is the tower equivalent radius [14]. For 500 kV two shield wires transmission line R_{tower}= 87.6668Ω, and for 500 kV single shield wire transmission line R_{tower}=84.9485 Ω.As it is observed in the above equation that the increasing of tower height increases the surge tower resistance.

C. Coupling Factor Calculations

The coupling factor (F) between the two shielding wires and each phase conductors can be calculated by the relation [15]:

$$F = \frac{\ln\sqrt{\frac{b_1 b_2}{a_1 a_2}}}{\ln\left(\frac{2h}{\sqrt{dr}}\right)}$$

(10)

Where a and b are the distances between each shielding wire to conductor and its reflection, h is height of ground wire and r is the radius of ground wire. In case of one shielding wire the coupling factor can be calculated as follows [16]:

$$F = \frac{\ln\left(\frac{b}{a}\right)}{\ln\left(\frac{2h}{r}\right)}$$

(11)

Table I gives the parameters of single and double circuits 500 kV transmission systems and the calculated coupling factor

TABLE I
COUPLING FACTOR FOR 500 KV T.L. SYSTEM

No. of shielding conductors	h (m)	Phase	a (m)	b (m)	F
1	52.42	A	a= 8.8864	b=97.3175	0.2394
		B	a=18.6936	b=88.1002	0.1550
		C	a=26.9112	b=78.4533	0.1070
2	58.2000	A	a_1= 12.2004 a_2= 23.3077	b1=104.6459 b2= 106.5137	0.3131
		B	a_1=23.1698 a_2=34.7131	b1=93.4420 b2=96.9513	0.2067
		C	a_1=34.3402 a_2=39.6693	b1=82.2584 b2=84.6218	0.1392

From table I it is noticed that conductors close to the shield wires have higher coupling coefficients (i.e. higher induced voltages) and consequently have lower voltages appearing across their supporting insulators. The induced voltage is calculated from the relation given in equation 12. Table II shows the induced voltage appears on the transmission line during transient over voltages on the shielding wires for phases A, B and C when grounding system contains 4 rods, 6 m length and 0.02 m radius, the soil resistivity ρ=100 Ωm, the mutual impedance factor M is taken 10% of one rod grounding resistance and the soil permittivity ε_r=9. The impulse peak current is varied as given in the table II. From this table it is noticed that the induced voltages on phases close to shielding wire are higher than the other phases. Also using two shielding wires increases the induced voltages and this will reduce the voltage appear across the tower insulators.

$$V_{induced} = F[i(t)Z_T(t) + V_{tower}(t)]$$

(12)

TABLE II
THE INDUCED VOLTAGE APPEARS ON THE TRANSMISSION LINE DURING TRANSIENT OVER VOLTAGES

Tower shielding	Impulse peak current	V_A(kV)	V_B (kV)	V_C(kV)
Single line	30 kA	682.93	442.35	305.29
Double line		918.80	606.48	408.52
Single line	100 kA	2126.7	1377.5	950.69
Double line		2866.7	1892.3	1274.6
Single line	150 kA	3157.9	2045.4	1411.7
Double line		4258.1	2810.7	1893.3
Single line	250 kA	5220.4	3381.3	2333.7
Double line		7040.9	4647.6	3130.6

III. BACK FLASH VOLTAGE (B.F.O.V)

The back flashover voltage for 500 kV transmission line systems can be calculated by the relation.

$$B.F.O.V(t) = (1 - F)[i(t)Z_T(t) + V_{tower}(t)] \quad (13)$$

Fig. 2 shows simulation of back flashover voltage appears across the tower grounding system and tower structure and the induced voltage appears on the transmission conductors.

Fig. 3 shows the B.F.O.V. as a function of time across 500 kV transmission system phases A, B, and C in case of two and single shield wires respectively. In case of tower grounding system has 4 rods, soil resistivity ρ=100 Ωm and impulse current =30 kA. As shown in Figs. 3 phase A has lower B.F.O.V. across its insulator string and phase C has the highest B.F.O.V. across its insulators.

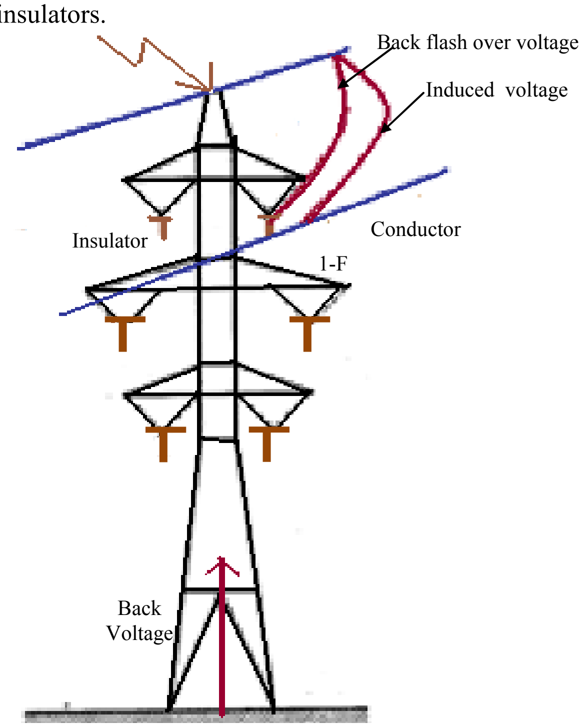

Fig. 2 Induced and back flashover voltages appears on the transmission line towers

As shown also in this figure the voltage appears on the grounding system is small compared with the voltage of tower surge impedance. It is approximately about 0.07% of the voltage appears on the tower surge impedance.

A. *Effect of Soil Resistivity on the Back Flashover Voltage*

To study the effect of soil resistivity variation on the ground surge impedance and back flashover voltage, the soil resistivity is changed between 50, 100, 200 and 300 Ωm. The ground system parameters are the rod length equals 6 m, number of rods are changed 4, 8 and 12 respectively, the radius of the driven rod is a=0.02 m and the soil permittivity ε_r=9. The peak value of the stroke current is 30 kA. Fig. 4 shows the relation between the soil resistivity and surge impedance of grounding system for two shield wires transmission line. In these calculations the effect of soil ionization is neglected according to IEEE guide lines [17, 19].

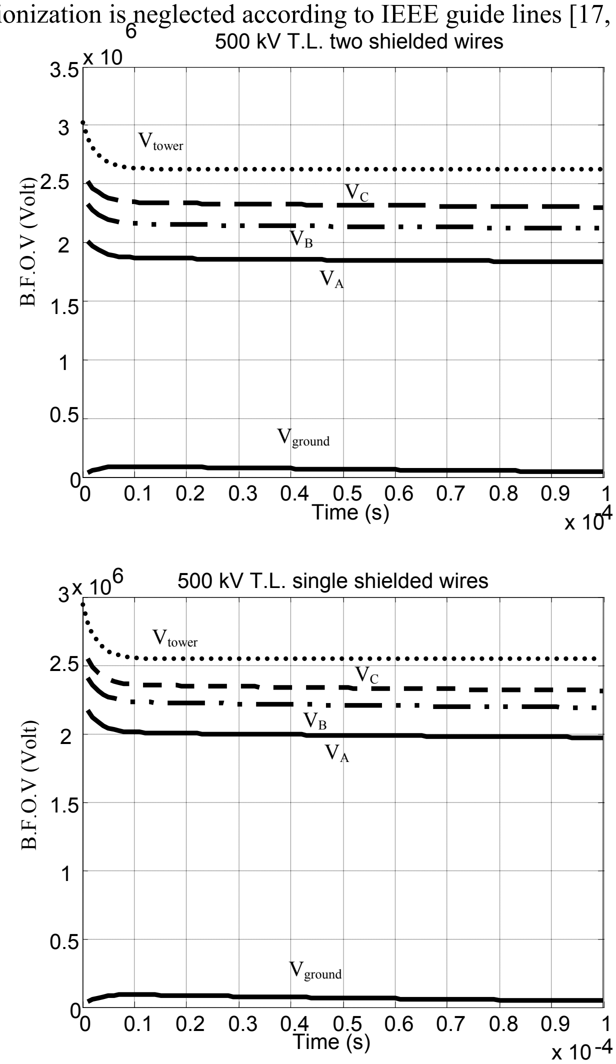

Fig. 3 the B.F.O.V. appears across 500 kV transmission system phases A, B, and C in case of two and single shield wires respectively. The amplitude

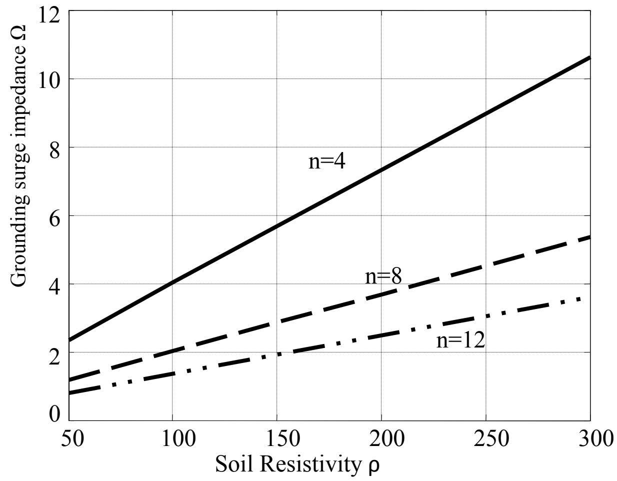

Fig. 4 the relation between the soil resistivity and surge impedance of grounding system for various numbers of rods

Table III gives the relation between B.F.O.V. and the soil resistivity ρ for the two types of 500 kV transmission lines towers when the impulse peak currents are 30kA and 250 kA, the grounding system contains 4 rods.

TABLE III THE RELATION BETWEEN B.F.O.V. AND SOIL RESISTIVITY KV T.L. FOR PHASES A, B AND C.

Impulse Peak current	No. of shielding wires	phase	Soil resistivity ρ			
			50 Ωm	100 Ωm	200 Ωm	300 Ωm
30 kA	B.F.O.V for two shielding wires kV	A	2004.7	2015.7	2037.6	2059.5
		B	2315.3	2328.0	2353.3	2378.6
		C	2512.2	2526.0	2553.4	2580.9
	B.F.O.V for single shielding wires kV	A	2158.1	2170.2	2194.5	2218.8
		B	2397.3	2410.8	2437.8	2464.7
		C	2533.6	2547.9	2576.4	2604.9
250 kA	B.F.O.V for two shielding wires kV	A	15355	15447	15629	15812
		B	17734	17840	18051	18262
		C	19242	19357	19586	19815
	B.F.O.V for single shielding wires kV	A	16488	16589	16792	16994
		B	18316	18428	18653	18878
		C	19357	19476	19714	19951

B. Influence of Grounding Rods Number on the B.F.O.V. and Surge Impedance

The number of rods of the tower grounding system is changed to be 4, 8, 12, 16 and 20 respectively. The soil resistivity is kept constant at 200 Ωm, each rod length is 6 m, radius of the driven rod is 0.02 m and the permittivity of the soil is $\varepsilon_r = 9$. The relation between the surge impedance versus the number of tower grounding system when impulse peak current = 30 kA is given in Fig. 5., Table IV gives the relation between B.F.O.V. and the number of grounding rods 4, 8, 12, 16 and 20 for the two types of 500 kV transmission lines towers for impulse peak current 30kA and 250 kA.

C. Effect of earth wire radius on the B.F.O.V.

In this section the earth wire radius is change and the B.F.O.V is calculated. The soil resistivity is kept constant at 200 Ωm, 4 rods are used in earthling system each rod length is 6 m, radius of the driven rod is 0.02 m and the permittivity of the soil is $\varepsilon_r = 9$. Table 5 shows the relation between B.F.O.V. and the radius of earth wire when impulse peak current takes the values of 30 kA and 250 kA respectively

From table V it's noticed that when the earth wire radius increases the B.F.O.V. decrease

IV. Conclusion

The main conclusions of this paper are:

1. Simplified approach is suggested to calculate B.F.O.V. of shielded high voltage transmission line tower and it is in agreement with the calculations done by ATP, given in reference [20].
2. The simplified method is used to investigate different factors affecting the transient B.F.O.V. such as earth wires radius, grounding system and soil resistivity.
3. From results it is noticed that:
   a) the coupling factor for the conductors close to the shielded wires have higher coupling coefficients (i.e. higher induced voltages)
   b) Grounding resistance has little effect on B.F.O.V. comparing with the surge impedance of the tower structure.
   c) Using two shielding wires reduces B.F.O.V. comparing with using single shielded wire.

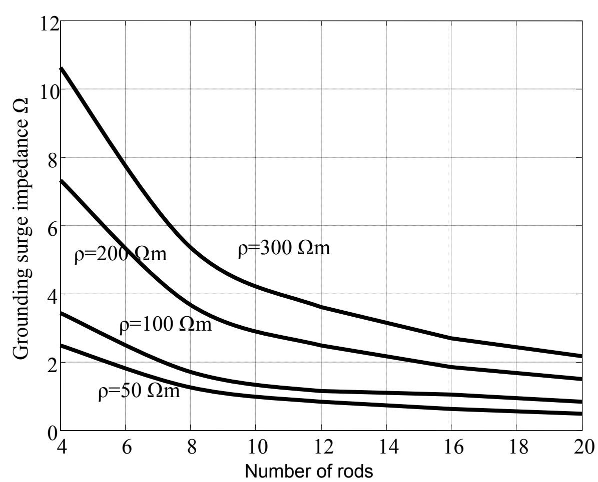

Fig. 5 relation between the surge impedance versus the number of tower grounding rods

TABLE IV THE RELATION BETWEEN B.F.O.V. AND THE NUMBER OF GROUNDING RODS FOR 500 KV TRANSMISSION LINE FOR IMPULSE PEAK CURRENT 30KA and 250 kA.

Impulse Peak current	No. of shielding wires	phase	Number of rods		
			4	8	12
30 kA	B.F.O.V for two shielding wires kV	A	2037.6	2013.5	2005.5
		B	2353.3	2325.5	2316.2
		C	2553.4	2523.2	2513.2
	B.F.O.V for single shielding wires kV	A	2194.5	2167.8	2158.9
		B	2437.8	2408.1	2398.3
		C	2576.4	2545.1	2167.8
250 kA	B.F.O.V for two shielding wires kV	A	15629	15428	15362
		B	18051	17819	17742
		C	19586	19334	19250
	B.F.O.V for single shielding wires kV	A	16792	16569	16495
		B	18653	18406	18324
		C	19714	19453	19366

TABLE 5 THE RELATION BETWEEN B.F.O.V. AND THE EARTH WIRE RADIUS FOR 500 KV TRANSMISSION LINE FOR IMPULSE PEAK CURRENT 30KA and 250 kA.

Impulse Peak current	No. of shielding wires	phase	Earth wire radius (cm)			
			0.4760	0.5	0.55	0.56
30 kA	B.F.O.V for two shielding wires kV	A	2037.6	2019.3	2011.7	2004.6
		B	2353.3	2334.1	2329.1	2324.4
		C	2553.4	2533.6	2530.2	2527.1
	B.F.O.V for single shielding wires kV	A	2194.5	2191.1	2184.4	2178.2
		B	2437.8	2435.6	2431.2	2427.2
		C	2576.4	2574.9	2571.9	2.5691
250 kA	B.F.O.V for two shielding wires kV	A	15629	15479	15421	15367
		B	18051	17892	17854	15367
		C	19586	19422	19396	19372
	B.F.O.V for single shielding wires kV	A	16792	16766	16714	16667
		B	18653	18636	18603	18572
		C	19714	19702	19679	19658

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