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Effect of Integrity of the Earthing System on the Rise of Earth Potential

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***Abstract*—**This paper investigates the effects of breaks in bonds, breaks in the earthing system and breaks in earth wire on the rise of the earth potential (EPR) in a substation and at the transmission tower bases using various models of an L6 tower. Different approaches were adopted to examine the integrity of the earthing system and the terminal towers. These effects were investigated to see the associated difference in the EPR magnitudes with respect to a healthy system at various locations. Comparisons of the computed EPR magnitudes were then made between the healthy and unhealthy system to detect any difference. The studies were conducted at power frequency for a uniform soil with different soil resistivities. It was found that full breaks in the double bond of the terminal towers increase the EPR significantly at the fault location, while they reduce EPR at the terminal tower bases. A fault on the isolated section of the grid can result in EPR values up to 8 times of those on a healthy system at higher soil resistivities, provided that the extended earthing system stays connected to the grid.

***Keywords*—**Bonding, earthing, EPR, integrity, system.

I. Introduction

EARTHING grid, bonding and earth wire connection to the towers of the extended earthing system form important components of the earthing system. Any damage or fault to these components / parts will result in the reduced integrity and performance of the earthing system. Many standards [1], [2] recommend the regular testing and checking of the earthing system for its continuous integrity and performance. Earthing system should be tested and inspected regularly to ensure that all necessary joints and connections are bonded and secure. In particular, earthing and bonding connections to equipment and earth grids should be checked. Neutral to earth connections needs to be verified also. In case of great reliance on the extended earthing systems or interconnections with other substations, such connections should also be checked. The conditions of reduced integrity and performance of the earthing system can result in increased magnitudes of the earth potential at various locations, especially at the fault position.
Such conditions should be checked and quantified for hazard limitation in substations as well as at transmission tower bases for increased performance of the earthing system. The integrity of the earthing system can be lost due to breaks in the bonds, breaks in the earthing grid, and breaks in the earth wire.

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II. Substation and Overhead Line Models

A. Model 1

Model 1 is shown in Fig. 1. It consists of three L6–type lines, 47 spans of 330m lengths per span with a total line length of 15.5km each. One end of the earth wire is terminated with a 100m by 100m earth grid having 100 meshes. At the other end of the line, the earth wire is left open-circuit. The earth wire is modelled as an ACSR conductor having a radius of 0.0143m, and is connected to the top of tower with sag included on each span. The earth grid conductor used has a radius of 0.01m. The height of the tower is 49.8m and it is represented by a single conductor of radius 0.1m. The tower base consists of cylindrical steel conductors having a radius of 0.02m and dimensions of 10m by 10m. The model is simulated with a fault current of 1A at the centre of the grid.

B. Models 2, 3 & 4

These models are shown in Fig. 2 and discussed in [3], [4]. They simulate the effect of earth wire disconnection at midspan locations for the expected increase in the earth potential at transmission tower bases. The current injection location is different in each case. Model 2 is a simplified representation of earthing system scenarios, which can be used for direct fault simulation at any location along the line. In Model 3, a phase conductor is also included to quantify the effect of the fault fed from the substation on one side only. The fault is fed from both sides in Model 4, as an earth grid is provided at both sides in this case. The earth grid shown in these models consists of only its perimeter conductor. For energisation purposes, a 1A current is used in all models. The earth wire is connected to the top of the towers and via the terminal tower to the earth grid in all models.

III. Analysis Results

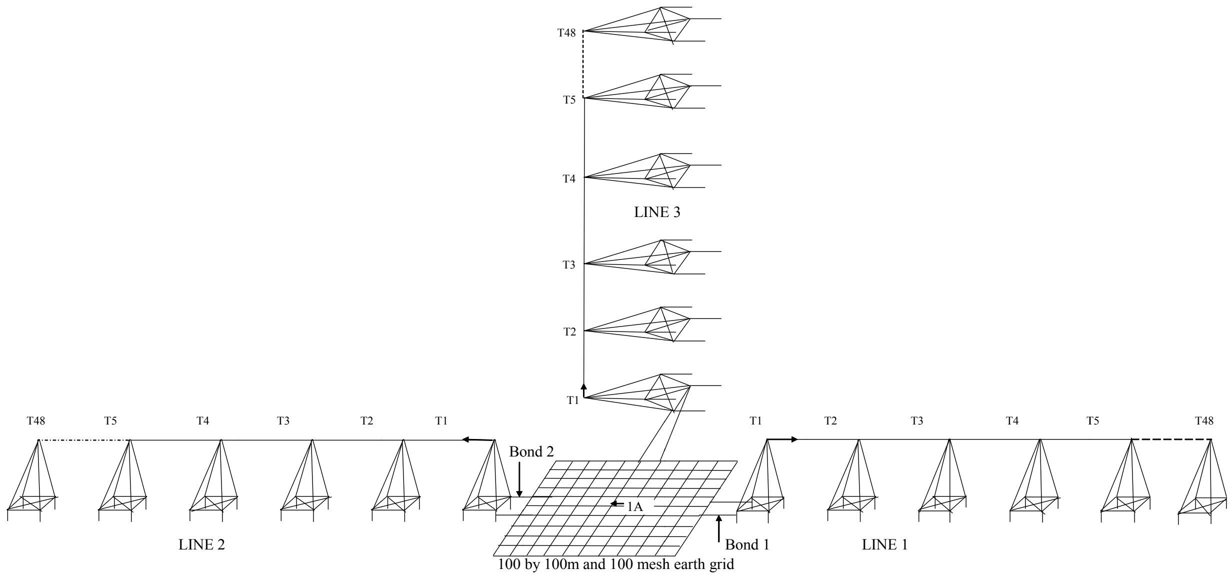
A. Model 1: Current Injected at the Center

Various scenarios were selected simulating Model 1, which are:

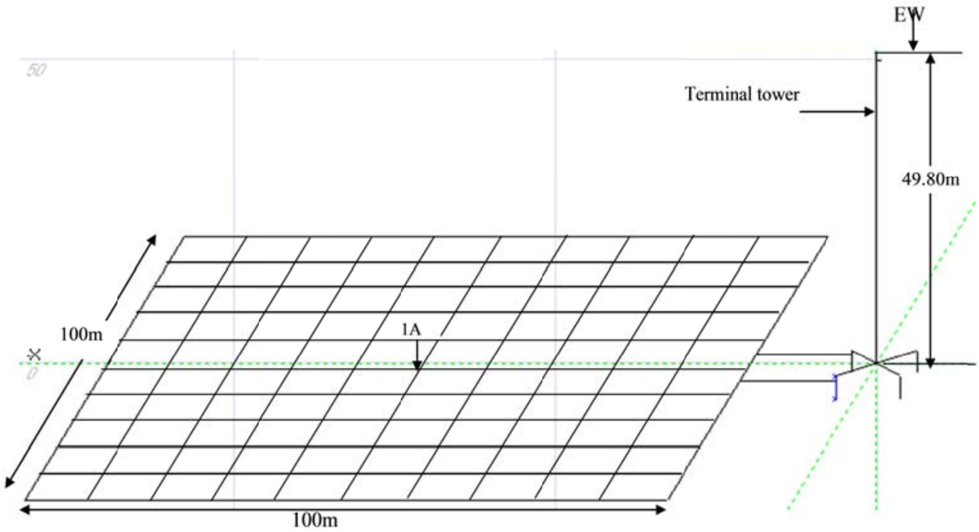
- Scenario I: Earth fault on a healthy system,
- Scenario II: Earth fault with one bonding conductor disconnected from the terminal tower,
- Scenario III: Earth fault with two bonding conductors disconnected from the terminal tower,
- Scenario IV: Earth fault with a section of the earthing grid

disconnected,

- Scenario V: Earth fault on the isolated section of the grid,

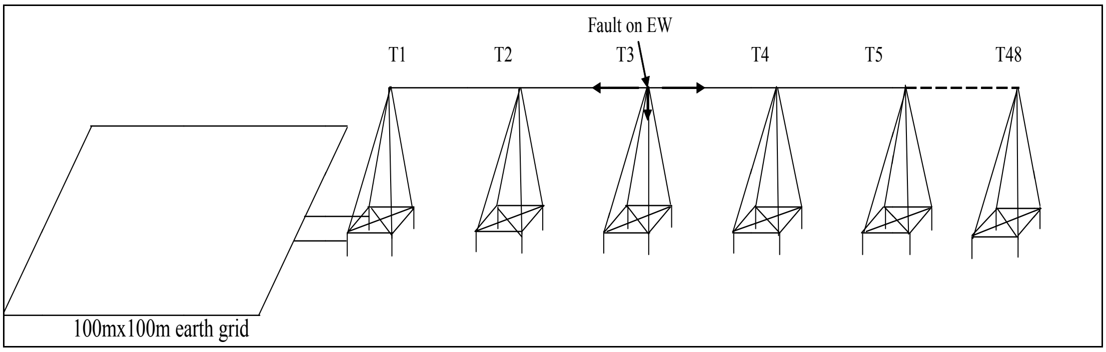


(a) Schematic model used in simulations

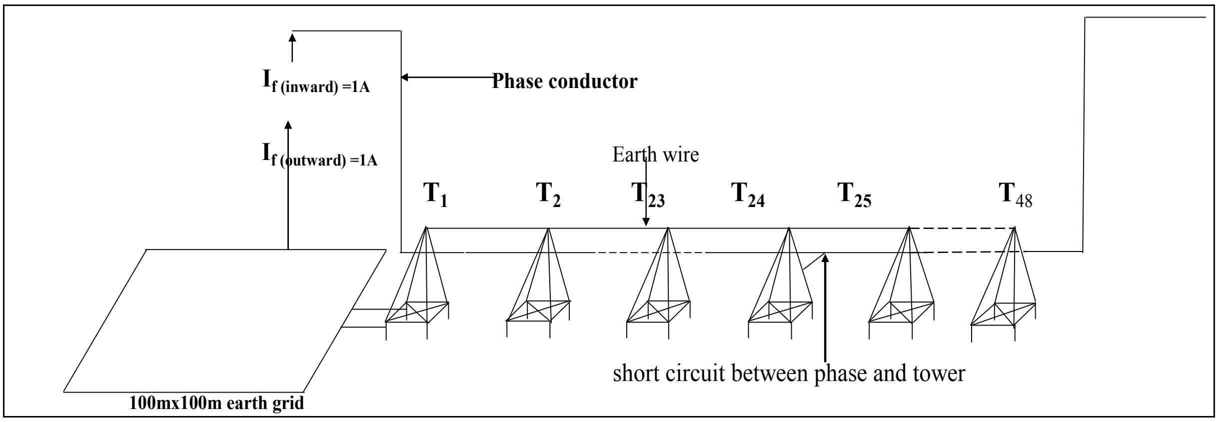


(b) Details of earth grid, tower base and terminal tower connection to the grid

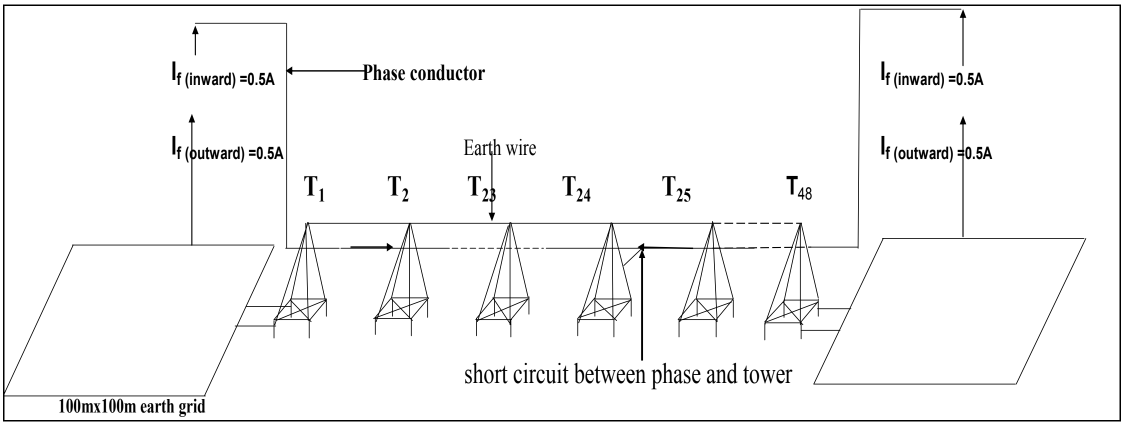
Fig. 1 Earth grid, terminal tower connection and line models used in simulations (Model 1)



(a) Single EW and grid with no meshes (Model 2)



(b) Single EW with phase conductor, earth grid at one end of the line (Model 3)



(c) Single EW with phase conductor, earth grid at both ends of the line (Model 4)

Fig. 2 Earth grid and line models [3], [4]

1. Scenario I: (Fault on a Healthy System)

In this case, an earth fault was simulated on a healthy earthing system by injecting a current of 1A at the centre of the grid. Fig. 3 shows the computed earth potential rise at the point of injection for various soil resistivities. The graph shows that the EPR magnitude increases with soil resistivity. At ρ=10Ωm, the computed EPR is 0.039V, which is increased to 0.258V and 1.20V as the earth resistivity is increased to 100 and 1kΩm respectively. At 10kΩm, the computed EPR reaches 5.36V. The EPR was also computed at the bases of the terminal towers of line 1, 2 and 3. These values show less variations to those computed in the earlier case for the point of injection. This may be reflected by the similar way of connection to the earthing grid and the less distance from the earthing grid. For these studies CDEGS [5] software was used.

A summary of the computed EPR magnitudes is shown in Table I for this scenario at different locations.

As expected it is also clear from Table I, that there is no difference in EPR magnitude at the terminal tower bases compared to those EPR values computed at the point of injection.

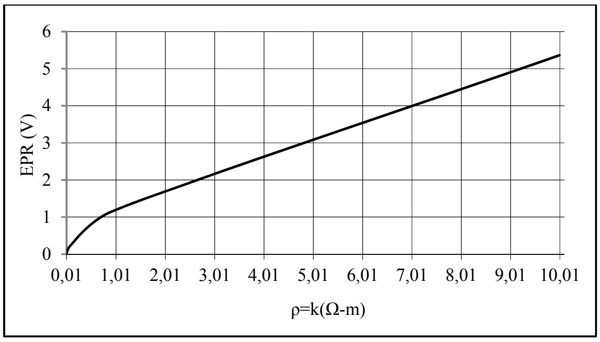


Fig. 3 Computed earth potential rise for a healthy system (Model 1, Scenario I)

TABLE I
COMPUTED EPR MAGNITUDES [SCENARIO I]

ρ (Ω-M)	POI*	TTL1*	TTL2*	TTL3*
10	0.039	0.037	0.037	0.037
100	0.258	0.256	0.256	0.255
1k	1.20	1.197	1.197	1.195
10k	5.357	5.355	5.355	5.354

* POI: Point of injection, TTL1: Base of the terminal tower (line 1) connected to grid, TTL2: Base of the terminal tower (line 2), TTL3: Base of the terminal tower (line 3)

2. Scenario II: (Effect of Single Bond Disconnection)

As shown in Fig. 1 (b), each terminal tower is bonded to the substation earth grid through two bonding conductors. In this scenario, the effects of disconnecting a single bonding conductor for each terminal tower were studied. The effect of the single bond disconnection from the terminal towers to the earth grid was investigated on the resultant EPR for:

1. Single bond of terminal tower of line 1 disconnected,
2. Single bond of terminal tower of line 1 and 2 disconnected, and
3. Single bond of terminal tower of line 1, 2 and 3 disconnected,

The computed EPR values have shown that disconnecting a bond of terminal tower of line 1 results in an increase in the EPR at the point of injection by 0.44% and 1.03% for ρ=1k and 10kΩm respectively. This study reveals that only a slight damage to the earthing system can result in variation in the EPR magnitudes, although these variations are negligible. The corresponding increase for the three lines disconnection is 0.52% and 1.05%. The maximum increase in the EPR at the base of the terminal towers was less than 1% for all studies of Scenario II.

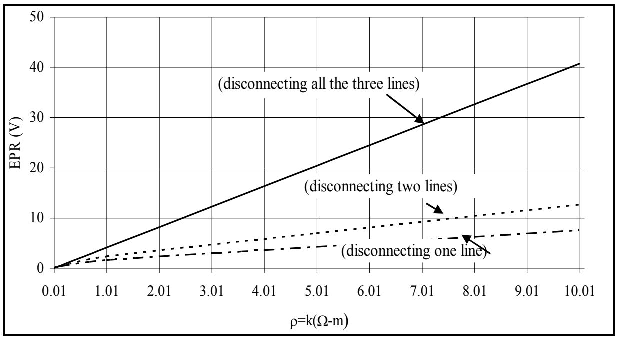
3. Scenario III: (Effect of Double Bond Disconnection)

The studies in Scenario II were repeated, but with two bonds disconnected from the terminal towers in this case. These effects were looked on the resultant increase in the EPR using three case studies. These are explained as:

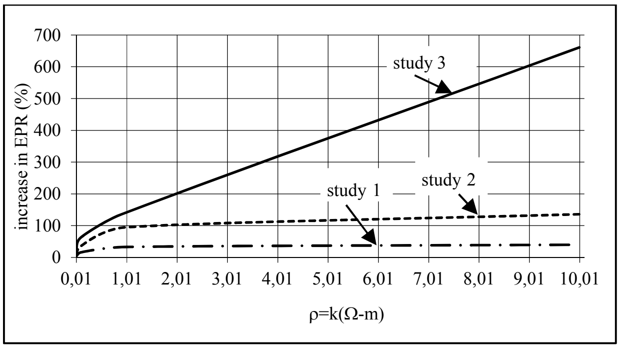
1. both bonding conductors of the terminal tower of line 1 disconnected,
2. both bonding conductors of the terminal tower of line 1 and 2 disconnected, and
3. both bonding conductors of the terminal towers of all the three lines disconnected

Fig. 4 (a) shows the corresponding effects of both bonds disconnection on the EPR magnitudes for studies 1, 2 and 3 respectively for various soil resistivities. For study 1, the computed EPR is 0.299V for ρ=100Ωm, which increase to 1.598V and 7.516V, when the soil resistivity is increased to 1k and 10kΩm. These magnitudes are higher by 16%, 33% and 40%, when compared with those equivalent magnitudes computed for Scenario I (healthy system). Table II summarises the computed EPR values for various bonding scenarios. It also gives the relative change in EPR when bonding conductors are removed. The EPR at the base of the terminal tower of line 1 is reduced by 53%, 75%, 89% and 94% due to its isolation from the earthing grid for ρ=10, 100, 1k and 10kΩm for study 1 results.

The computed EPR is higher for studies 2 and 3, when compared with study 1. This is also clear from Fig. 4. These magnitudes are higher by 36%, 95%, 135% for study 2 and by 63%, 242% and 661% for study 3 for the corresponding values of ρ=100, 1000 and 10kΩm to those computed for a healthy system (Fig. 3). The higher increase in case of study 3 is explained by removing the significant contribution of the extended earthing system. At the bases of the disconnected terminal towers from the grid, the corresponding EPR reduces for all the three studies.



(a) Computed EPR due to two bonds disconnection



(b) Relative EPR increase in percent at the point of current injection

Fig. 4 Effect of two bonds disconnection on the computed EPR (Scenario III)

TABLE II
COMPUTED EPR (V) [SCENARIO I AND III]

	Scenario I	Scenario III		
ρ (Ω-m)	Healthy System	1/% rise	2 /% rise	3/% rise
10	0.039	0.040 / 2.6	0.042 / 7.7	0.04 / 12.8
100	0.258	0.299 / 15.9	0.35 / 35.7	0.42 / 62.4
1k	1.20	1.598 / 33.2	2.34 / 95.2	4.1 / 241.6
10k	5.357	7.516 / 40.3	12.6 / 136	40.8 / 661.6

Fig 4 (b) shows the relative increase in EPR for the three case studies of Scenario III at the point of current injection. A summary of the EPR at the terminal tower bases for Scenario III under the conditions of studies 1, 2 and 3 indicated that the largest decrease at terminal tower occurs when only line 1 is disconnected. This is due to the excessive rise of EPR on the grid for other two cases. This high EPR causes a higher potential decrease at the terminal tower 1. Fig. 5 shows the corresponding decrease at the bases of terminal towers of line 1, 2 and 3 respectively. Table III gives the relative change of EPR at the tower bases compared with the “healthy system”.

4. Scenario IV: (Effect of Disconnecting a Section of Earthing Grid)

For these studies, initially a section of 30m x 30m of the earthing grid was disconnected from the rest of the grid, while all the three lines were left connected to the earthing grid through the terminal towers. The corresponding EPR magnitudes were computed for various soil resistivities at the earthing grid as well as at the terminal tower bases. The computed magnitudes were higher by 0.4% and 1.06% for a soil resistivity of 1k and 10kΩm at the earthing grid, when compared with those computed for a "healthy system" (Scenario I). The computed EPR at the bases of the terminal towers were similar to those at the grid. This study reveals that losing a small section of the grid will have no significant effect on the rise of the earth potential at the grid, provided that the fault does not occur at the isolated section of the grid.

TABLE III
DECREASE IN EPR IN % AT THE BASES OF TERMINAL TOWERS [SCENARIO III]

ρ (Ω-m)	Study 1	Study 2		Study 3		
	TT1	*TT1*	*TT2*	*TT1*	*TT2*	*TT3*
10	53.89	52.28	52.38	50.67	50.67	63.34
100	75.11	70.78	70.78	65.94	65.94	78.04
1k	88.89	83.04	83.04	72.18	72.18	82.78
10k	93.35	89.17	89.17	71.95	71.95	82.03

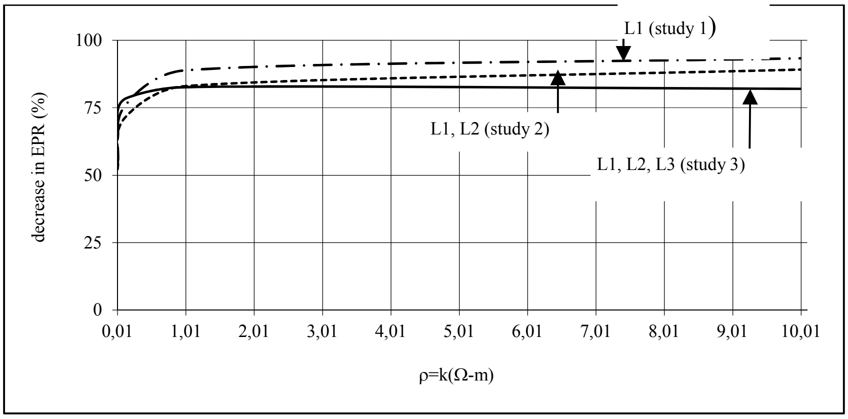


Fig. 5 Relative decrease in EPR at the base of terminal towers of line 1, Study 1: Disconnecting one line, Study 2: Disconnecting two lines, Study 3: Disconnecting all lines

To quantify the effect of a larger disconnecting section of the grid disconnection on the EPR, further studies were carried out. Fig. 6 shows the computed EPR for the case study, where a 50m x 50m section of the grid is disconnected of the healthy system. The fault was energised at the section of the grid connected to the extended earthing system. The comparison of the computed EPR with the healthy system shows that these values are higher by 12%, 5% and 3.2% for ρ=100, 1k and 10kΩm. It is important to mention that isolating a large section of the grid sometimes involves the isolation of the extended earthing system from the grid, which can result in significant increase in EPR at the grid and reduced at the isolated terminal tower bases. In that case, the situation will become similar to that for which studies were carried out in Scenario III depending upon the number of the disconnected lines from the grid. Table IV gives a summary of the computed EPR values for small and larger section of the earthing grid disconnected for various soil resistivities.

5. Scenario V: (Effect of Fault on the Isolated Section of the Grid)

For these studies, the fault was simulated by energising the 50mx50m disconnected section of the grid using 1A current and the computations were carried out at the point of current injection. During these studies, the extended earthing system was kept connected to the rest of the grid. Fig. 7 shows the computed EPR magnitudes for these studies with respect to a healthy system. These values are much higher, when compared to those computed for a healthy system. The corresponding values are higher by 123%, 343% and 866% at ρ=100, 1k and 10kΩm.

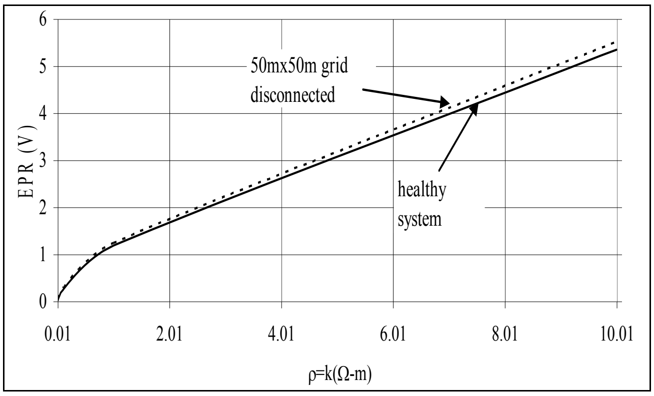


Fig. 6 Effect of disconnecting a section of the earthing grid on EPR (Scenario IV)

TABLE IV
COMPUTED EPR FOR SCENARIO IV

ρ (Ω-m)	30mx30m disconnection	50mx50m disconnection
	EPR (V)	EPR (V)
10	0.386	0.0463
100	0.257	0.289
1k	1.205	1.256
10k	5.414	5.527

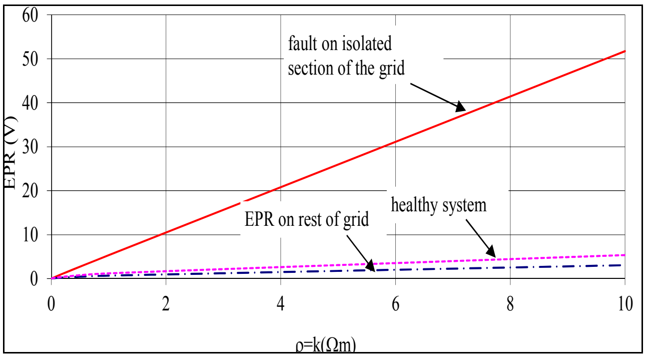


Fig. 7 Computed EPR Vs soil resistivity for Scenarios I and V

B. Models 2, 3 and 4: (Current Injected at Various Locations)

Computations of EPR distribution at the tower bases were carried out using the models shown in Fig. 2, to quantify the effect of the earth wire disconnection at various tower locations along the line. These computations were carried out for a uniform soil resistivity of 100Ωm and at power frequency.

1. Results for Model 2

The computed EPR distribution at tower bases for Model 2 is shown in Fig. 8, when tower 24 is faulted. The earth wire is disconnected midspan between towers 9 and 10 and then between 19 and 20 for these computations. It can be seen that, when the earth wire is disconnected between tower 9 and 10, the EPR magnitude is increased by 93% at tower 10 and then reduces quickly close to zero at tower 9, when compared with the case of the connected earth wire. At the faulted tower base, little change in EPR magnitude can be seen. Similarly, when the earth wire is disconnected between tower 19 and 20, the computed EPR is increased by 86% and 18% at towers 20 and 24 respectively, when compared with the case of the connected earth wire. In this case, the computed EPR is higher at tower bases for a number of spans on the right hand side of the line from tower 19 onwards. At tower 19, the EPR magnitude reduces quickly to zero, when compared with the uniform distribution of EPR for the case of the connected earth wire. This study reveals that the location of the breaks in the earth wire with respect to the faulted tower plays an important role in controlling the EPR at tower bases.

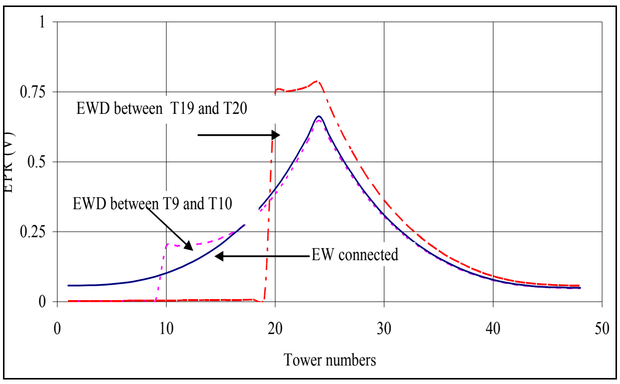


Fig. 8 Effect of break in earth wire on EPR at tower bases (Model 2)

2. Results for Model 3

In this model an earth wire as well as a phase conductor was used. Fig. 9 shows the corresponding EPR distribution at tower bases, when injecting a current of 1A at the phase conductor from the substation end. The effect of the earth wire disconnection is different in this case, when compared with the previous study. This results in higher EPR magnitudes at towers 9, 20 and even at tower 24 (faulted tower in this case). At towers 9 and 20, these magnitudes are higher by 674% and 17% respectively, when the earth wire is disconnected midspan between tower 9 and 10. The increase extends a long section of the line from tower 21 until tower 1. At tower 24, no significant increase was recorded. For the case study, when the earth wire is disconnected midspan between tower 19 and 20, the computed EPR is higher by 240%, 196% and 57% at the bases of towers 9, 20 and 24 respectively, when compared with the connected earth wire case study. In this case, the computed EPR distribution is higher for the whole line length, when compared with the connected earth wire case. At the grid and the terminal tower location (right hand side), the difference in magnitudes reduces considerably for both studies i.e. earth wire disconnected between towers 9 and 10, and towers 19 and 20. In the latter case, the difference tends to zero.

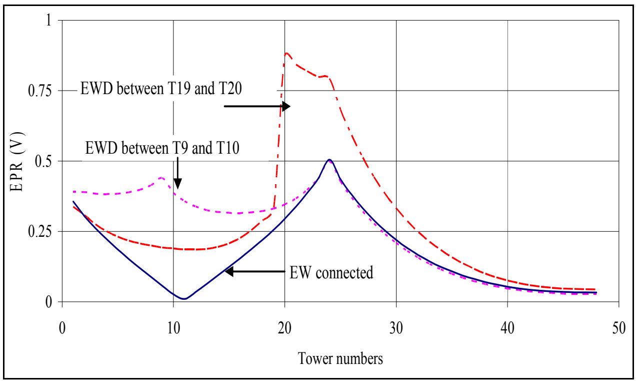


Fig. 9 Effect of break in earth wire on EPR at tower bases (Model 3)

3. Results for Model 4

Model 4, shown in Fig. 2 (c) includes substation earth grids connected to the earth wire at both ends of the line via the terminal towers. The phase conductor is energised from both ends of the line with a current of 0.5A resulting in a current of 1A injected at the point of fault (Tower 24). Fig. 10 shows the effect of the earth wire disconnection at midspan on the resultant EPR distribution for this model. The increase in the EPR is less at towers 9 and 20 compared with the previous study of Model 3, for the earth wire disconnection case study between tower 9 and 10. For the earth wire disconnected between tower 19 and 20 case study, the EPR magnitudes are higher by 178%, 140% and by 37% at towers 9, 19 and 24 respectively, compared with the case of the connected earth wire.

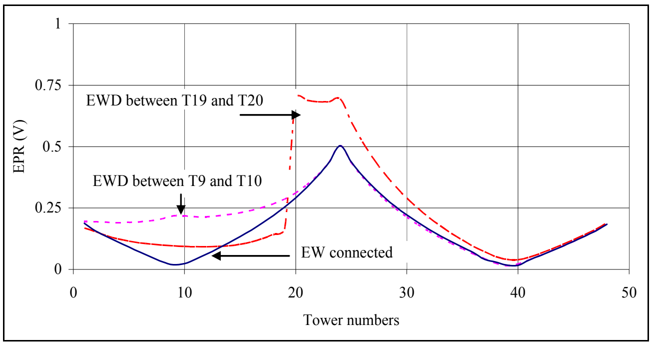


Fig. 10 Effect of breaks in earth wire on EPR at tower bases (Model 4), (substation plus sources at both ends)

A summary of the computed earth potential at various towers and models is given in Table V for the corresponding effects of the earth wire disconnection at different locations and with tower 24 being faulted.

It is clear from Table V that the earth wire disconnection results in significant increase in EPR magnitudes at the faulted and adjacent towers for all the three type of models, when the earth wire is disconnected close to the faulted tower (i.e. at tower 19).

TABLE V
SUMMARY OF THE COMPUTED EPR AT VARIOUS TOWER LOCATIONS

Conditions	Computed EPR (V) at various towers		
EW connected	Model 2	Model 3	Model 4
T9	0.09	0.057	0.019
T10	0.103	0.027	0.024
T19	0.353	0.256	0.254
T20	0.403	0.295	0.291
T24	0.663	0.505	0.503
Conditions: EW Disconnected between T9 and T10			
T9	0.004	0.439	0.218
T10	0.198	0.387	0.218
T19	0.338	0.332	0.286
T20	0.385	0.345	0.311
T24	0.648	0.499	0.504
Conditions: EW Disconnected between T19 and T20			
T9	0.004	0.193	0.096
T10	0.005	0.190	0.094
T19	0.009	0.334	0.164
T20	0.749	0.874	0.699
T24	0.784	0.792	0.694

IV. CONCLUSIONS

Integrity of the earthing system was investigated using a number of scenarios. Various case studies were undertaken taking into account the breaks in bonds, earth wire and the earthing gird at terminal substations.

From the results of the studies carried out, the following points are concluded:

- Single breaks in the double bond of the terminal towers do not affect the rise of the earth potential significantly.
- Full breaks in the double bond of the terminal towers increase the earth potential significantly at the fault location, while they reduce EPR at the terminal tower bases. For worse case EPR values up to 6.6 times of the healthy system can be expected at higher soil resistivity at the fault location, but a reduction up to 94% at the terminal tower bases can result.
- The effect of disconnection of a small section of the earthing grid, while the rest of the system is connected to the lines is found to have no significant change in EPR compared with that of a healthy system. However, disconnection of a large section of the grid involving the loss of the extended earthing system will have significant effects on the EPR.
- A fault on the isolated section of the grid can result in EPR values up to 8 times of those on healthy system at higher soil resistivities, provided that the extended earthing system stays connected to the grid.
- In case of external earth fault, the break in earth wire at midspan, close to the fault can result in significant increase in EPR at the adjacent as well as at the faulted tower.
- For faults fed from the substation, the break in earth wire at midspan can result in higher EPR at tower bases, if the break happens either close to the substation or to the faulted tower.
- The effect of soil resistivity on the rise of earth potential is significant during fault conditions.

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