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Analysis of the Over-Voltages Produced by Lightning Strokes in the Power Transmission System in the Southern Region of Saudi Arabia

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Abstract: This study deals with the simulation of lightning strokes and their effects on power network in the southern region of Saudi Arabia. The network consists of main generating stations, substations and the power transmission lines. The transient performance of the system has been investigated using the EMTP (Electro Magnetic Transient Program). Some surges were introduced to the network ~~as~~ in the form of lightning strokes. The power system responses to such surges were monitored and the results were recorded for studies and more analysis. These results reflect the behavior of the network under such sever conditions, in which the weak point of the system can be discovered. Then some protection devices have been suggested to maintain the continuity of the supply and power delivery. The paper also contains analytical study of the obtained results, which helps in suggesting certain solutions to avoid excessive high over-voltages in the mentioned power network.

Key words: Over-voltages, lightning strokes, three phases, transmission system, remote bus-bars, peak system voltage

INTRODUCTION

The cities and suburbs of the southern region of the Kingdom of Saudi Arabia are located on the Sarawat mountains chain (east of the Red Sea). The heights of these mountains are up to 2000m and 3000m above the sea level, which makes the area liable to yearly rainy seasons, usually longer in duration than in the other regions of the country. The power transmission lines of the Saudi Electric Company (SEC) of the south region are erected on top of these mountains. The rainy intervals are accompanied by lightning strokes and some times by thunderstorms which expose those lines to frequent lightning strokes. The transmission network there is of level 132 kV, which makes the over-voltages produced in the system by the ingression of lightning strokes higher in magnitude and more hazardous than the internally produced over-voltages.

The aim of this study is to simulate and analyze the over-voltage state of the system, when it is subject to external surges. Then suggestions to improve the performance of the network are made. The stations and bus-bars which will experience the highest over-voltages during lightning strokes have been considered in more details.

LIGHTNING PHENOMENA AND SURGE

Lightning stroke to ground is composed of: the leader which is the first visible process in the development of a discharge to earth; it is a weakly-luminous column propagating from cloud base to ground, not continuously but in a series of steps between which there is a pause of some 50 microsecond or so. The step length is in the range of 10-200 m and the mean velocity lies in the range of approximately 0.3% - 7% of the velocity of light. The mechanism of producing the discharge can be found in many literatures [1, 2].

A lightning surge may take place on the system at any point and at any time. A lightning surge of the form shown in Fig. 1 can be represented as [3, 4]:

$$v(t) = V\left(e^{-\alpha t} - e^{-\beta t}\right)$$

Where: α and β are constants; they determine the wave shape. V determines the magnitude of the lightning represented as a voltage surge.

The waveform of the surge voltages impressed on the insulation of a system due to lightning stroke may vary rather widely because of the reflection and deflection phenomenon in the line and mode or position of the stroke. The front and tail times do nonetheless tend to fall within reasonably closely defined limits.

The equations that determine the reflection and deflection phenomena in the transmission lines can be summarized as: [5]

The characteristic (or surge) impedance of the transmission system Z_0 is given by:

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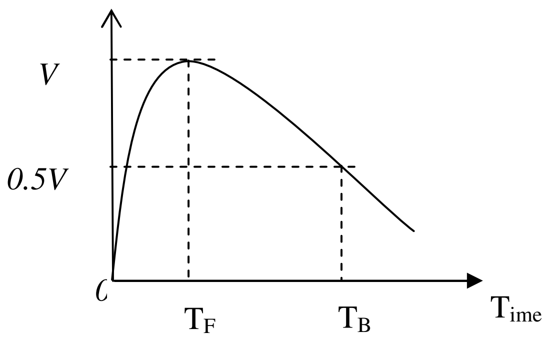

Fig. 1: Lightning surge function representation

$$Z_0 = \sqrt{(L/C)}$$

Where L is the line inductance in H/m; and C is the line capacitance in F/m.

The Velocity of Propagation is found to be:

$$u = \sqrt{(1/LC)}$$

The reflection and transfer coefficients can be given as:

$$V^+e^{-Kr} + V^-e^{Kr} = (Z_r / Z_0)\{V^+e^{-Kr} - V^-e^{Kr}\}$$

Where Kr is the reflection coefficients and can be written as:

$$K_r = (Z_r - Z_0)/(Z_r + Z_0)$$

V^+ is the voltage forward wave;

V^- is the voltage backward wave;

and Z_r is the termination impedance of the receiving end.

The transfer coefficient in matrix form for three phase or higher systems is:

$$[K_T]_m = 2 * [Z_m] * [Y_i]$$ at terminal i of line m.

Where: $[Z_m]$ is the surge impedance matrix of line m;

$[Y_i]$ is the sum of all surge admittance matrices of the multi-phase circuits connected to node i;

And the reflection coefficient is:

$$[K_R]_m = [K_T]_m - [U]$$

Where [U] is the unity matrix.

THE TRANSIENT ANALYSIS OF THE TRANSMISSION NETWORK

The Electromagnetic Transient Program (EMTP) has been used for simulation and analysis purposes. EMTP has become widely used in the utility industry and other applications[6-10]. In this work its capability in simulating lightning surges and transient over-voltages calculations are being implemented.

The 132 kV transmission network of the southern region of Saudi Arabia of year 1995, is shown in Fig. 2. Lightning current surge of the form 3/50µs with amplitude of 4 kA is injected at once into all of the three phases (one of the phases is at its peak system voltage). The process is repeated into all of the bus-bars of the system, one at a time except generator buses.

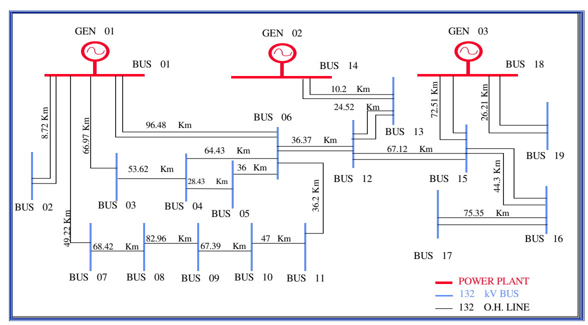

Fig. 2: Lay out of power transmission network[11]

The maximum over-voltages all over the system bus-bars are recorded as shown in Table 1.

Table 1: Maximum over-voltages on the system produced by the lightning stroke without any protection devices. (The column to the most left indicates the buses under surge)

	BUS 01	BUS 02	BUS 03	BUS 04	BUS 05	BUS 06	BUS 07	BUS 08	BUS 09	BUS 10	BUS 11	BUS 12	BUS 13	BUS 14	BUS 15	BUS 16	BUS 17	BUS 18	BUS 19
BUS02	3.89	7.06	3.83	2.85	2.82	2.61	3.85	3.80	3.70	4.45	3.82	2.59	2.35	2.46	1.59	1.72	2.09	1.33	1.89
BUS03	2.42	3.81	7.14	4.98	4.91	3.18	4.05	3.83	4.28	4.32	4.21	2.84	3.87	3.86	2.12	2.62	3.15	2.15	2.43
BUS04	1.92	2.82	4.97	5.10	5.02	3.25	2.86	3.71	3.38	3.17	3.20	2.89	3.31	3.56	2.11	2.71	3.14	2.18	2.32
BUS05	2.66	2.79	4.89	5.02	7.12	2.73	2.75	4.05	3.34	2.68	2.70	2.62	3.29	3.04	1.91	2.45	2.74	1.87	2.09
BUS06	1.80	2.58	3.17	3.25	2.73	2.78	2.64	3.27	2.70	2.73	2.75	2.50	2.81	2.98	1.57	1.89	2.03	1.43	1.75
BUS07	2.44	3.84	4.06	2.87	2.77	2.65	7.13	6.94	6.61	6.36	6.02	2.41	2.68	2.61	1.72	1.97	2.12	1.43	1.56
BUS08	2.39	3.76	3.81	3.71	4.04	3.26	6.92	7.17	6.83	6.54	6.43	3.05	3.09	3.62	2.10	2.30	3.15	1.75	2.00
BUS09	2.34	3.65	4.26	3.37	3.32	2.69	6.58	6.82	7.18	6.88	6.77	3.15	2.99	3.25	2.17	2.02	3.30	1.81	2.06
BUS10	2.54	4.41	4.30	3.16	2.67	2.72	6.34	6.54	6.88	7.16	7.06	2.96	2.75	3.22	1.97	1.62	2.28	1.70	2.07
BUS11	2.35	3.78	4.19	3.19	2.69	2.74	6.00	6.43	6.77	7.07	7.13	2.47	2.76	2.95	1.57	1.98	2.07	1.43	1.74
BUS12	1.88	2.56	2.82	2.89	2.62	2.50	2.40	3.05	3.16	2.97	2.47	3.65	4.11	4.48	1.99	1.98	2.83	1.77	2.34
BUS13	1.67	2.32	3.86	3.31	3.29	2.81	2.66	3.09	3.00	2.76	2.76	4.11	4.72	5.09	2.16	2.23	3.23	2.30	2.61
BUS15	1.30	1.56	2.10	2.11	1.91	1.57	1.71	2.11	2.19	1.98	1.57	1.99	2.16	2.30	4.51	4.46	7.60	3.79	5.82
BUS16	1.43	1.68	2.60	2.70	2.44	1.88	1.95	2.30	2.02	1.63	1.98	1.97	2.22	2.48	4.46	10.73	18.8	4.13	5.78
BUS17	1.56	2.04	3.13	3.12	2.73	2.02	2.09	3.14	3.30	2.28	2.07	2.81	3.21	3.48	7.59	18.85	19.8	6.42	10.39
BUS19	1.44	1.88	2.44	2.34	2.12	1.78	1.57	2.03	2.09	2.11	1.77	2.36	2.64	3.02	5.85	5.81	10.4	5.09	6.48

Table 2: Maximum over-voltages on the system, produced by lightning stroke when surge arresters are connected to every bus in the network

	BUS 01	BUS 02	BUS 03	BUS 04	BUS 05	BUS 06	BUS 07	BUS 08	BUS 09	BUS 10	BUS 11	BUS 12	BUS 13	BUS 14	BUS 15	BUS 16	BUS 17	BUS 18	BUS 19
BUS02	1.94	1.83	1.67	1.63	1.66	1.62	1.67	1.65	1.62	1.62	1.60	1.55	1.48	1.80	1.22	1.23	1.36	1.15	1.28
BUS03	1.49	1.63	1.83	1.70	1.65	1.67	1.57	1.52	1.64	1.67	1.63	1.63	1.69	1.86	1.26	1.51	1.56	1.28	1.31
BUS04	1.26	1.49	1.68	1.82	1.66	1.59	1.56	1.57	1.61	1.65	1.63	1.65	1.71	2.05	1.54	1.55	1.61	1.56	1.63
BUS05	1.50	1.49	1.70	1.70	1.83	1.66	1.48	1.63	1.66	1.59	1.60	1.65	1.69	1.82	1.40	1.50	1.58	1.50	1.52
BUS06	1.65	1.68	1.71	1.74	1.69	1.80	1.63	1.69	1.69	1.67	1.69	1.73	1.73	2.18	1.48	1.52	1.58	1.37	1.58
BUS07	1.49	1.63	1.61	1.50	1.52	1.35	1.83	1.72	1.69	1.70	1.68	1.34	1.46	1.49	1.14	1.26	1.24	1.11	1.18
US08	1.39	1.58	1.39	1.56	1.58	1.49	1.72	1.83	1.72	1.70	1.68	1.58	1.55	1.61	1.31	1.32	1.53	1.23	1.23
BUS09	1.31	1.51	1.58	1.59	1.57	1.64	1.69	1.72	1.83	1.72	1.69	1.62	1.54	1.55	1.36	1.20	1.55	1.19	1.30
BUS10	1.36	1.58	1.65	1.63	1.52	1.47	1.69	1.70	1.72	1.83	1.72	1.56	1.61	1.62	1.25	1.21	1.40	1.18	1.24
BUS11	1.29	1.55	1.64	1.62	1.60	1.53	1.70	1.68	1.69	1.72	1.83	1.60	1.68	1.76	1.30	1.31	1.38	1.25	1.28
BUS12	1.51	1.62	1.66	1.68	1.63	1.72	1.46	1.67	1.66	1.67	1.63	1.82	1.77	2.74	1.54	1.55	1.62	1.66	1.64
BUS13	1.32	1.55	1.68	1.69	1.66	1.71	1.46	1.62	1.63	1.63	1.64	1.78	1.82	3.28	1.41	1.59	1.64	1.72	1.69
BUS15	1.23	1.36	1.55	1.45	1.56	1.45	1.37	1.49	1.60	1.59	1.36	1.49	1.64	1.81	1.84	1.68	1.71	2.43	1.76
BUS16	1.08	1.10	1.27	1.35	1.31	1.25	1.12	1.20	1.35	1.25	1.17	1.34	1.56	1.59	1.66	1.85	1.69	1.73	1.66
BUS17	1.01	1.09	1.51	1.50	1.35	1.35	1.05	1.16	1.45	1.44	1.28	1.35	1.46	1.38	1.64	1.65	1.84	1.66	1.64
BUS19	1.17	1.36	1.52	1.60	1.49	1.36	1.22	1.35	1.43	1.42	1.23	1.45	1.64	1.65	1.78	1.64	1.68	2.56	1.82

Table 3: Maximum over-voltages on the system, produced by lightning stroke when surge arresters are connected to bus 2, 3, 5, 7, 9, 11, 15, 16, 17, and 19 only

	BUS 01	BUS 02	BUS 03	BUS 04	BUS 05	BUS 06	BUS 07	BUS 08	BUS 09	BUS 10	BUS 11	BUS 12	BUS 13	BUS 14	BUS 15	BUS 16	BUS 17	BUS 18	BUS 19
BUS02	1.94	1.83	1.67	1.80	1.70	1.70	1.67	2.02	1.64	1.88	1.63	1.59	1.50	1.83	1.23	1.25	1.39	1.15	1.30
BUS03	1.48	1.63	1.83	2.21	1.67	1.85	1.62	1.65	1.65	2.30	1.63	1.84	2.16	2.30	1.32	1.50	1.53	1.33	1.47
BUS04	1.80	1.70	1.79	5.10	1.79	2.63	1.68	2.50	1.69	2.28	1.71	2.38	2.83	3.00	1.54	1.61	1.61	1.54	1.62
BUS05	1.53	1.53	1.70	2.23	1.83	1.83	1.53	1.97	1.68	1.79	1.62	1.90	2.16	2.27	1.42	1.57	1.57	1.51	1.49
BUS06	1.80	1.71	1.73	3.20	1.72	2.78	1.68	2.67	1.69	2.38	1.72	2.50	2.78	2.98	1.54	1.52	1.61	1.40	1.59
BUS07	1.49	1.63	1.61	1.55	1.52	1.42	1.83	2.80	1.72	2.58	1.72	1.34	1.66	1.67	1.20	1.35	1.36	1.14	1.23
BUS08	1.49	1.63	1.62	1.82	1.64	1.68	1.82	7.17	1.82	2.79	1.72	1.83	1.82	1.84	1.33	1.29	1.58	1.18	1.33
BUS09	1.37	1.57	1.62	2.00	1.59	1.75	1.71	2.78	1.83	2.80	1.72	1.79	1.72	1.68	1.48	1.34	1.60	1.27	1.39
BUS10	1.48	1.63	1.67	1.80	1.61	1.71	1.73	2.78	1.82	7.16	1.83	1.73	1.97	1.94	1.34	1.31	1.52	1.22	1.40
BUS11	1.33	1.56	1.65	1.86	1.61	1.55	1.69	2.52	1.72	2.83	1.83	1.75	1.97	1.95	1.29	1.36	1.37	1.22	1.30
BUS12	1.67	1.69	1.71	2.72	1.71	2.50	1.63	2.52	1.71	2.56	1.70	3.65	4.11	4.48	1.69	1.60	1.65	1.61	1.67
BUS13	1.67	1.68	1.75	3.01	1.75	2.79	1.69	2.49	1.69	2.41	1.72	4.11	4.72	5.09	1.72	1.66	1.67	1.97	1.67
BUS15	1.23	1.37	1.54	1.46	1.56	1.46	1.39	1.54	1.60	1.75	1.36	1.52	1.80	1.82	1.84	1.68	1.71	2.43	1.76
BUS16	1.08	1.10	1.28	1.34	1.31	1.25	1.12	1.20	1.35	1.26	1.17	1.34	1.61	1.62	1.66	1.85	1.69	1.73	1.66
BUS17	1.01	1.09	1.51	1.52	1.35	1.35	1.05	1.16	1.46	1.45	1.29	1.35	1.47	1.39	1.64	1.65	1.84	1.66	1.64
BUS19	1.18	1.37	1.52	1.72	1.49	1.36	1.22	1.36	1.43	1.42	1.23	1.52	1.82	1.83	1.78	1.64	1.68	2.56	1.82

The same above simulation is repeated once more with surge arresters (zinc-oxide gapless and 238kV threshold voltage). The results are recorded in Table 2. For a reduced cost scheme, a third simulation test has been made with surge arresters present on some bus-bars; those who experienced the highest over-voltages in Table 1; (they are 2, 3, 5, 7, 9, 11, 15, 16, 17, and 19). The over-voltage results of this condition are posted in Table 3.

The results obtained show that the system is not secure against direct high current lightning strokes. Some of the buses show extremely high over-voltages during the simulation , as in bus 16, bus 17 and bus 19. That is obvious since all protection means are ignored, and those terminals are remote and floating. This outcome is also an indicator, pointing to those weak buses in the system.

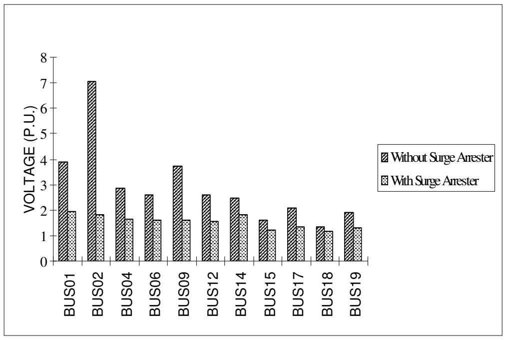

Fig. 3: Maximum over-voltages produced by a lightning stroke on bus 02

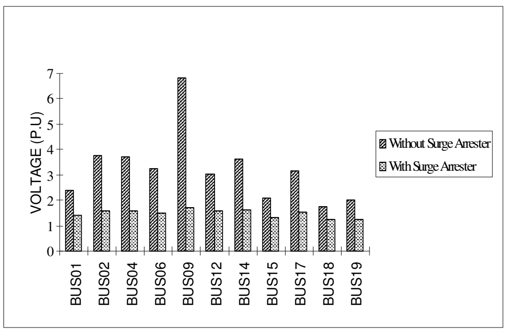

Fig. 4: Maximum over-voltages produced by a lightning stroke on bus 08

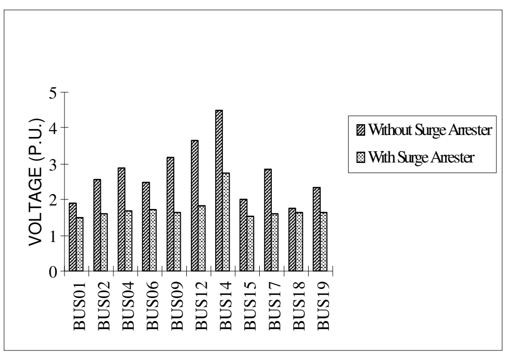

Fig. 5: Maximum over-voltages produced by a lightning stroke on bus 12

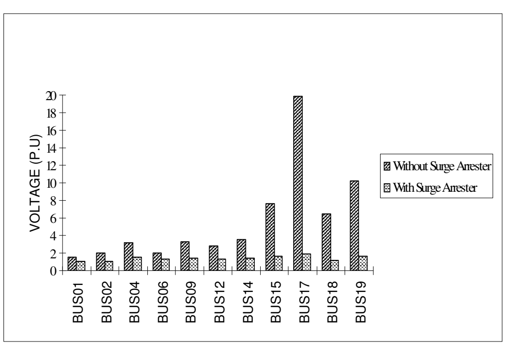

Fig. 6: Maximum over-voltages produced by a lightning stroke on bus 17

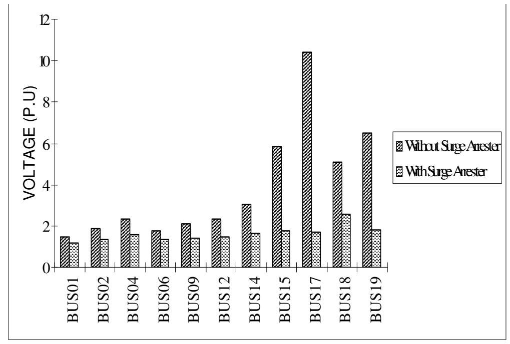

Fig. 7: Maximum over-voltages produced by a lightning stroke on bus19

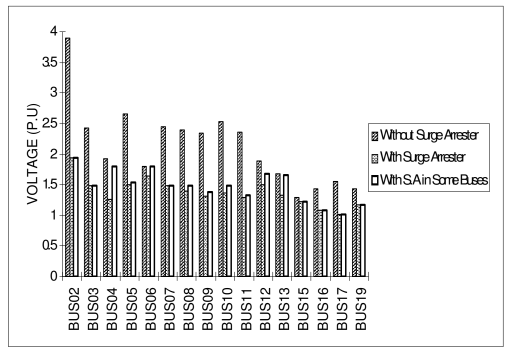

Fig. 8: Maximum over-voltages on the generator bus (Bus 01) for the three cases.

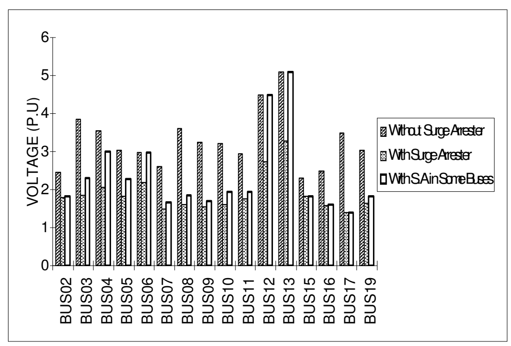

Fig. 9: Maximum over-voltages on the generator bus (Bus 14) for the three cases.

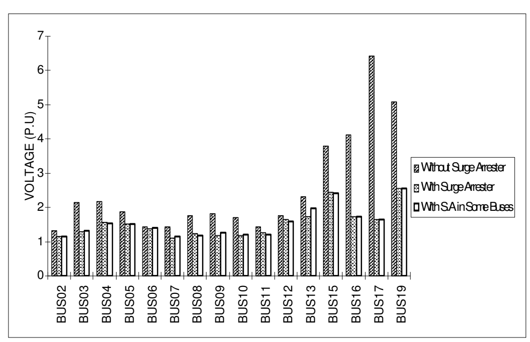

Fig. 10: Maximum over-voltages on the generator bus (Bus 18) for the three cases.

Figures 3–7 show the results as bar-chart of some selected buses. These Figures are drawn to compare between the over-voltages with and without the protective surge arresters.

Figures 8-10, show a comparison between the maximum over-voltages on the generator buses.

The use of surge arrestors all over the network has reduced the produced over-voltages to an acceptable levels (less than 2 pu) sustaining for a duration of time less than or equals 3μs.

However, the use of surge arrestors at some selected buses in the network (those which experienced the highest over-voltage level) has improved the network protection against direct lightning strokes, even though, some buses still have slightly high over-voltages.

CONCLUSION

The network of the southern region of the Kingdom of Saudi Arabia has been studied for the problem of over-voltages occur during lightning strokes. When a lightning stroke hits one of the three phases of the transmission system at its system peak voltage, it will experience the highest over-voltage with respect to the other phases. Radial branches suffer higher over-voltages than the loop circuits. Bus-bars with higher number of branch circuits will experience lower over-voltages.

The simulation that has been carried out using the EMTP software determined the network over-voltages at different buses with and without protective surge arresters. The process has been repeated for different lightning stroke locations. It is found that for secure and reliable power system, surge arresters should be installed on the transmission networks at the nodes that are more susceptible to lightning strokes.

Also, the results show that the remote buses on the power transmission systems are vulnerable to high over-voltages produced by sudden surges. The other bus-bars, whom are tightly linked to other circuits in the network, are having a lower over-voltages. This indicates that the remote bus-bars must be either connected to some other nodes in the system, in order to close their loop circuits, or at least they should be equipped with satisfactory protection devices against any sudden surges.

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