TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 12, No. 8, August 2014, pp. 5814 ~ 5826
DOI: 10.11591/telkomnika.v12i8.6033

Reliability Analysis of Surge Arrester Location Effect in High Voltage Substations

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Abstract

High voltage substations as pivotal sections of power network play an important role in power network because of supplying electrical energy for consumers. In recent years with increment of electricity consumption and complexity of power system, the substation stability and protection against various faults or overvoltages has been a big concern. Surge arresters as protective device has the responsibility of attenuating overvoltage due to lightning or switching occurring in transmission or distribution system. Absence or failure of arresters inside or near substations can lead to load interruption and great outage in the system. Therefore their presence is indispensable. Demonstrating the surge arresters presence necessity and evaluating their failure impact during normal operating condition and overvoltage in different scenarios of arrester location and lightning surge position in view point of EMTP simulation and reliability technique is the purpose of this paper.

Keywords*: surge arrester, EMTP-RV, high voltage substation, reliability indices, minimal cut set*

1. Introduction

High voltage substations as a key part of power systems connect generation sources to distribution networks. Fast growth of electrical energy demand with the development of power systems makes these substations more important. Therefore, substation reliability is an important concern from both utility and customer points of view [1]. Substations are always subject to various overvoltages such as switching and lightning that may cause substations failure. The substation failure can lead to the outage of so many loads in the power system, which can be catastrophic to the system [2]. The most dangerous overvoltage is due to lightning surge which its frequency range is from 10 kHz to 3MHz. If lightning strikes the lines or the towers adjacent to a substation, causes back-flashover, the overvoltage wave propagates at the substation and can damage substation equipment such as transformer dramatically. Between 5% to 10% of the lightning-caused faults are thought to result in permanent damage to power system equipment [3].

Surge arresters are being applied to system to mitigate the overvoltage. As novel protection devices against overvoltages with outstanding operational performance, metal oxide surge arresters (MOA) were developed 20 years ago and are now being extensively applied in power systems to lower the insulation level and ensure long time reliability of the high voltage equipment [4]. Their nonlinear resistance characteristic protects equipment against overvoltages which may exceed basic lightning impulse insulation level (BIL). Arresters can be located on selected points of the network to obtain the required control of overvoltages [5], particularly inside and near the substations. Thus, surge arresters increase the reliability of the substations during the occurring of overvoltages especially due to lightning surge.

Ideal surge arresters should be open circuit during normal operating condition of the system and short circuit during the overvoltages. But the insulation behavior of MOA may be subject to changes due to different degradation mechanisms that can be categorized as impact from continuous operating voltage stress, humidification caused by deficiency in structure and poor sealing, impulse current stress of inside partial discharge, effects of atmospheric surface contamination, etc [4]. These factors can increase the leakage current of arresters and incline them to be short circuit especially in the end of their life. Short circuit behavior of surge arresters in normal condition of system reduces the reliability of substations. Also open circuit behavior of surge arresters during overvoltage reduces the reliability greatly. In general, modern surge

Received March 30, 2014; Revised May 10, 2014; Accepted May 26, 2014

arresters utilizing ZnO blocks are very reliable apparatus with a low failure rate. A published number for distribution arresters is 0.1% failures per year, while for high voltage arresters the estimated failure rate is even lower [6]. It can be concluded that failure of arresters can affect the substation reliability and can cause severe harm to substation reliability or great outage in the network. In addition, location of surge arresters affects the equipment terminal voltage and substation reliability. They are often installed in the place where the incoming line connects to the substation and on transformer feeders.

For the investigation of surge arresters influence on the HV substations reliability, first it will be seen from the simulation analysis point of view by Electro Magnetic Transient Program (EMTP-RV). Then it will be analyzed by mathematical methods given for calculating of reliability. Dehak substation which is a 230/63 kV substation in Neka, Iran, is selected as a case study. Assessments prove, absence or failure of arrester can impose a serious problem to substation and lead to long time load unavailability.

2. System Modeling

Dehak, a 230/63 kV and one breaker and half substation in Neka, Iran, is considered as case study. It has eight feeders consists of six line feeders and two transformer feeders. The single line diagram of this substation is shown in Figure 1.

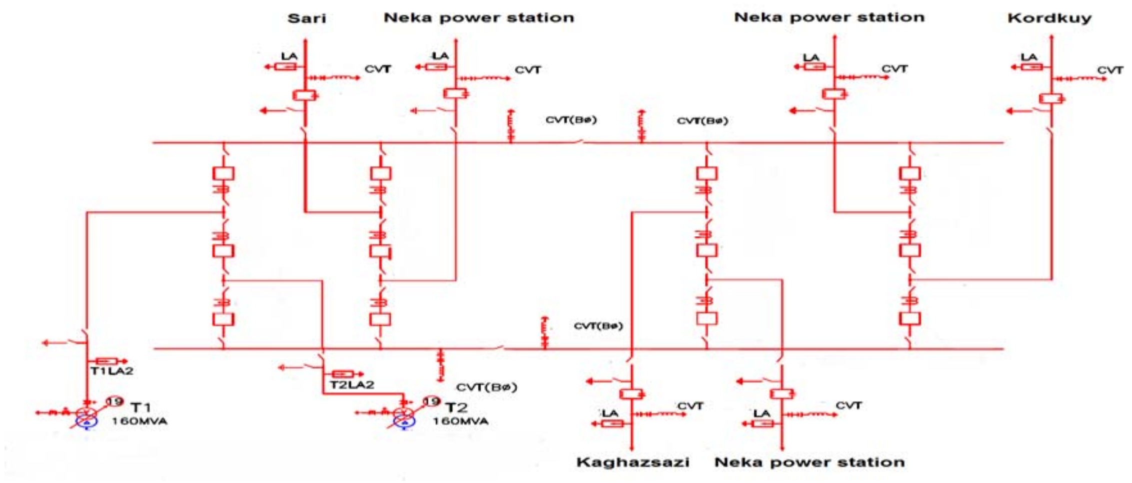


Figure 1. Dehak Substation Single Line Diagram

In order to obtain actual results from simulation of the substation, particularly in transient condition, proper models of substation equipment and other components should be applied to simulation. In this section various elements of the considered system with their models are introduced.

Owing to inherent distributed nature of transmission lines, frequency dependent (FD) line is used to model transmission lines connected to the substation. Electrical parameters of these lines that must be inserted into the line data of FD lines are shown in Table 1. In this table, R_0, L_0 and C_0 are zero sequence parameters and R_1, L_1 and C_1 are positive sequence parameters.

Table 1. Electrical Parameters of Lines

Data	Neka	Sari	Kordkuy	Kaghazsazi
R_0 (Ω/km)	0.3184	0.0892	0.4467	0.3255
L_0 (mH/km)	3.8276	2.3679	2.7315	3.2446
C_0 (μF/km	0.00473	0.00827	0.005348	0.00607
R_1 (Ω/km)	0.0612	0.032	0.1058	0.0529
L_1 (mH/km)	1.294	0.9261	2.0094	0.9844
C_1 (μF/km)	0.00888	0.0127	0.008775	0.0115

The choice of tower model in analyzing lightning surge in the power system is very important. The steel towers are usually represented as a single conductor distributed parameter line terminated by a resistance representing the tower footing impedance [7]. Constant parameter (CP) line is used to simulate single conductor of tower model. 160Ω and speed of light are determined for towers surge impedance and wave velocity as the principal parameters of CP line.

Dielectric strength of line insulators under lightning conditions depend on the impulse waveshape, magnitude and polarity. A lightning-impulse voltage, with a magnitude that exceeds the critical flashover (CFO), may still not last long enough to carry streamers all the way to complete insulation breakdown [8]. In order to model insulator string, flashover switch as an element in EMTP-RV is used.

Lightning surge waveform has considerable influence on the overvoltage inducing on substation equipment. The lightning surge is modeled by a current and a parallel resistance (Cigre model). The resistance value is taken to be 400Ω, which was derived by Bewley [9]. The standard impulse waveform (1.2/50) with the peak value of 150kA is used for modeling of lightning surge.

The appropriate modeling of a surge arrester is significant for insulation coordination studies in order to extract reliable estimations. For this reason, several frequent-dependent models of ZnO surge arresters, using the physical and the electrical data given by the manufacturer, have been proposed, in a way that the model simulation results correspond to the actual behavior of the arrester [10]. In the related simulation, ZnO surge arrester is represented by IEEE recommended model which is demonstrated in Figure 2. This model contains non-linear resistances in two locations which are separated by an RL filter. This RL filter provides impedance that differs between the cases of fast surges and slow surges [11]. Table 2 shows IEEE model parameters and other characteristics of arresters used in Dehak substation. In this table, V_r and I_d are arrester rated voltage and discharge current respectively. Besides of surge arrester model, the v-i characteristic of surge arresters also specifies the behavior of them. Their characteristics should be nonlinear such that surge arrester current rises as overvoltage occurs and abate to very small value when overvoltage decays. The arrester lead length at the top and at the bottom must be considered to account for the effects of additional voltage rise across the lead inductance. A lumped element representation with an inductance of 1μH/m will be sufficient [7].

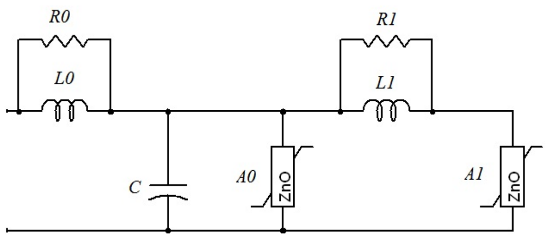


Figure 2. IEEE Model of Surge Arresters

Table 2. IEEE Model Parameters and Characteristics of the Arresters

Parameter	Value
R_1 (Ω)	143.325
L_1 (μH)	33.075
C (nF)	0.04535
R_0 (Ω)	220.5
L_0 (μH)	0.441
V_r (kV)	198
I_d (kA)	10

Under lightning overvoltage, substation equipment such as circuit breaker, disconnector, power transformers and instrument transformers can be approximated with capacitors. Equivalent capacitances of the substation equipment are shown in Table 3.

Table 3. Equivalent Capacitance of Substation Equipment

Equipment	Equivalent capacitance (pF)
Power transformer	2000
Current transformer (CT)	200
Capacitive voltage transformer (CVT)	5000
Disconnector	150
Circuit breaker	500

Busbar and interconnections between the substation equipment should be modeled by distributed lines or lumped inductance. A model of lumped parameter inductance, its unit value being 1μH/m, is usually taken for sections, the lengths of which do not exceed 15m [12], otherwise distributed line is used. Dehak substation has a long busbar more than 100m, therefore CP model line should be used to represent that in simulation.

3. Simulation Results

By means of data and elements models given in previous section, Dehak substation was simulated by EMTP-RV software with the application of lightning surge to many points such as inside the substation, substation entrance and line phase.

Simulation shows overvoltage waveshape and its amplitude basically depends on location of lightning strike and position of surge arresters. Since transformers on transformer feeders and capacitor voltage transformers (CVT) on the entrance, are more important than other equipment, their voltages during applying lightning surge have been measured and their values are shown in Table 4 for different cases of lightning stroke location and surge arresters position. Simulation shows if lightning strikes the point which is farther than 250 m from the substation, overvoltage wave attenuates drastically and its amplitude decreases greatly under the transformer BIL (850kV) and the CVT BIL (1050kV) and therefore can not harm them. According to this table, the places of surge arresters are:

a) Absence of arrester (A)
b) Presence of arrester in substation entrance (E)
c) Presence of arrester in transformer feeder (T)
d) Presence of arrester in substation entrance and transformer feeder (E+T)

Table 4. Maximum Induced Voltage due to Lightning

Lightning stroke location	**Maximum induced voltage (kV)**							
	CVT				Transformer			
	A	E	T	E+T	A	E	T	E+T
Inside the substation	2823.20	854.59	2640.10	818.11	4331.1	3454.40	999.83	814.22
Substation entrance	3071.5	1040.60	3071	1038.30	4101.3	1273.10	921.16	575.65
50 m from substation	1028.1	522.50	735.65	518.91	1179.20	808.96	506.03	454.28
100 m from substation	890.25	492.62	742.49	483.44	1216.6	819.09	498.59	443.94
150 m from substation	809.62	481.17	775.66	484.41	1283	836.51	492.72	444.14
200 m from substation	711.20	466.75	695.40	465.18	1145	845.90	499.47	457.55
250 m from substation	596.78	462.55	596.14	462.55	936.61	800.44	506.02	480.60
300 m from substation	569.61	442.43	569.32	442.46	824.05	782.70	532.66	528.73

Shaded values indicate to the cases in which overvoltage exceeds the BIL.

4. Reliability Assessment Method

In previous sections, role of surge arresters and their locations impact were investigated. Now, reliability techniques are used to analyze surge arresters effects from the viewpoint of reliability. The equations which are needed for calculating reliability are given in [13] in terms of failure rate (λ), repair time (r) and unavailability (U) for series and parallel systems that may contain one, two or more components.

For substations reliability evaluation, several techniques have been suggested in different researches such as Markov modeling [14], minimal cut set [15] and Monte Carlo simulation [16]. Cut set and especially minimal cut set technique can be an appropriate approach for calculating reliability indices. Cut set is a disconnecting set that breaks a path between a load node and a source node and minimal cut set is a cut set which has no subsets [17]. A minimal cut set is the smallest set of components that can cause a system to fail if they fail [18]. In this technique failure modes of the system should be found. The failure modes of the system are identified either visually or using the minimal cut set method [13]. Some of these methods are introduced by [1] and [17].

On the basis of cut set technique, by tracing the path starting from source to load point, failure modes can be found. For simplicity of finding failure modes, the substation configuration can be displayed by graph which includes nodes as each node represent an element.

Since surge arresters should act completely different during normal operating and overvoltage conditions, thereby reliability evaluation has to be performed for each of these two conditions separately. An ideal surge arrester should be open circuit during normal operating condition and short circuit during overvoltages. Possible reasons for failure of an arrester include the following [6]:

a) Overloading of the active elements by energy or current.
b) Moisture ingress.
c) Partial flashover of one or several units in a multiunit arrester caused by external pollution, birds or high overvoltages.
d) Thermal instability due to the effect of heavy external pollution.
e) High temporary overvoltages.
f) Damage of some blocks in one or several units due to energy and current discharges which leads to power frequency overload of the remaining part of the arresters.
g) Mechanical overloading which leads to an electrical failure.

Arresters tend to be short circuit when they enter fatigue phase of their life. Failure during impulse passage may occur due to overloading or quality problems such as significant inhomogeneities in the ZnO blocks, poor electrode adhesion to the material, insufficient surface insulation, etc [6].

Before evaluating of substation reliability for the cases of different surge arrester locations, the parameters used in this analysis are introduced in Table 5.

Table 5. Parameters used in the Reliability Analysis

Parameter	Description
λ_{sc}	short circuit failure rate of arresters during normal condition of system (fail per year)
r_{sc}	repair time of arresters due to short circuit failure (hour)
λ_{oc}	open circuit failure rate of arresters during overvoltage (fail per year)
λ_1, λ_2	busbars failure rate (fail per year)
r_1, r_2	busbars repair time (hour)
$\lambda_3,\ldots,\lambda_{14}$	circuit breakers failure rate (fail per year)
$r_3,\ldots,r_{14}$	circuit breakers repair time (hour)
λ_{15}, λ_{16}	power transformers failure rate (fail per year)
r_{15}, r_{16}	power transformers repair time (hour)
t_{ov}	overvoltage duration
λ_{L1}	Annual number of lightning stroke to inside the substation due to shield wire failure
λ_{L2}	Annual number of lightning stroke to substation entrance due to shield wire failure
λ_{L3}	Annual number of lightning stroke to points between 50 m to 250 m from substation due to shield wire failure
P_{L1}	Probability of annual lightning stroke to inside the substation due to shield wire failure
P_{L2}	Probability of annual lightning stroke to substation entrance due to shield wire failure
P_{L3}	Probability of annual lightning stroke to points between 50 m to 250 m from substation due to shield wire failure

4.1. Modeling of Substation Reliability due to Surge Arrester Location

In this part, various cases of surge arrester locations with their graphs and equations are given.

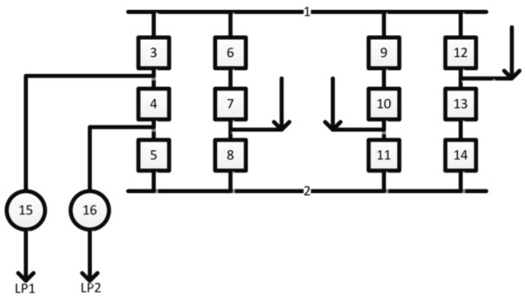
a. Absence of arrester (A)

1) Normal operating condition

It is worth pointing out that annual lightning stroke and probability of annual lightning stroke are corresponding and have same values.

The graph of this condition is shown in Figure 3.The minimal cut sets obtained are as follows:

First order: 15
Second order: 1-2, 2-3, 1-5, 3-5, 3-4, 1-4
The average failure rate, average unavailability and average outage time are calculated using "(1)", "(2)" and "(3)" respectively.



Square and circle are symbols of circuit breaker and transformer respectively.

Figure *3*. Graph of normal operating condition in the case of absence of arrester

$$\lambda_{A1} = \lambda_{15} + \lambda_1\lambda_2(r_1 + r_2) + \lambda_2\lambda_3(r_2 + r_3) + \lambda_1\lambda_5(r_1 + r_5)$$
$$+ \lambda_3\lambda_5(r_3 + r_5) + \lambda_3\lambda_4(r_3 + r_4) + \lambda_1\lambda_4(r_1 + r_4) \quad (1)$$

$$U_{A1} = \lambda_{15}r_{15} + \lambda_1\lambda_2 r_1 r_2 + \lambda_2\lambda_3 r_2 r_3 + \lambda_1\lambda_5 r_1 r_5$$
$$+ \lambda_3\lambda_5 r_3 r_5 + \lambda_3\lambda_4 r_3 r_4 + \lambda_1\lambda_4 r_1 r_4 \quad (2)$$

$$r_{A1} = U_{A1} / \lambda_{A1} \quad (3)$$

2) Overvoltage condition
The graph of this condition is shown in Figure 4.

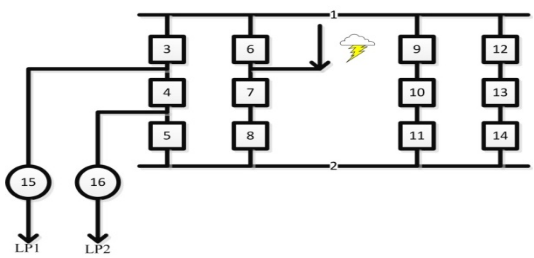


Figure 4. Graph of Overvoltage in the Case of Absence of Arrester

According to simulation outcomes demonstrated in Table 4, striking the lightning surge to the points inside the substation, substation entrance and between 50 m to 250 m from the substation in the case of absence of arrester can damage the equipment like CVT and transformer and lead to substation failure to supply load. Load point reliability indices of this case are calculated using "(4)", "(5)" and "(6)".

$$\lambda_{A2} = \lambda_{L1} + \lambda_{L2} + \lambda_{L3} \quad (4)$$

$$U_{A2} = \lambda_{A2} r_{15} \quad (5)$$

$$r_{A2} = U_{A2} / \lambda_{A2} \quad (6)$$

b. Presence of arrester in substation entrance (E)

1) Normal operating condition

Figure 5 demonstrates the graph of this condition. As well as busbar, breaker and transformer that were considered in pervious case, in this case surge arrester failure is involved in reliability estimation. The minimal cut sets are as follows:

First order: 15

Second order: 1-2, 2-3, 1-5, 3-5, 3-4, 1-4

Third order: 17-18-19

The load point reliability indices are given by "(7)", "(8)" and "(9)".

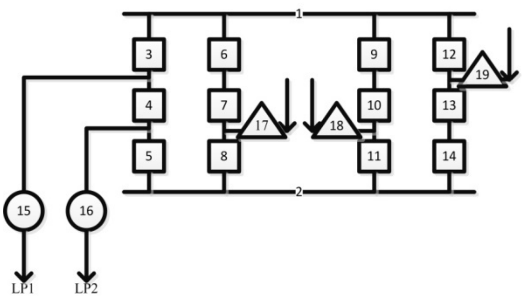
$$\lambda_{E1} = \lambda_{15} + \lambda_1\lambda_2(r_1+r_2) + \lambda_2\lambda_3(r_2+r_3) + \lambda_1\lambda_5(r_1+r_5) + \lambda_3\lambda_5(r_3+r_5) + \lambda_3\lambda_4(r_3+r_4) + \lambda_1\lambda_4(r_1+r_4) + \lambda_{sc}^3(3r_{sc}^2) \quad (7)$$

$$U_{E1} = \lambda_{15}r_{15} + \lambda_1\lambda_2 r_1 r_2 + \lambda_2\lambda_3 r_2 r_3 + \lambda_1\lambda_5 r_1 r_5 + \lambda_3\lambda_5 r_3 r_5 + \lambda_3\lambda_4 r_3 r_4 + \lambda_1\lambda_4 r_1 r_4 + \lambda_{sc}^3 r_{sc}^3 \quad (8)$$

$$r_{E1} = U_{E2} / \lambda_{E2} \quad (9)$$

2) Overvoltage condition

In order to calculate the load point reliability indices of this condition, all the possibilities of substation failure have to be considered by referral to simulation results given in Table 4. Shaded values in that table indicate to the cases in which overvoltage exceeds the BIL, so that such values can be causer of substation failure. Failure rate of each possibility can be seen in Table 6 in which SC and OC stand for short circuit and open circuit status of arrester respectively.



Triangle is symbol of surge arrester

Figure 5. Graph of Normal Operating Condition in the Case of Presence of Arrester in Substation Entrance

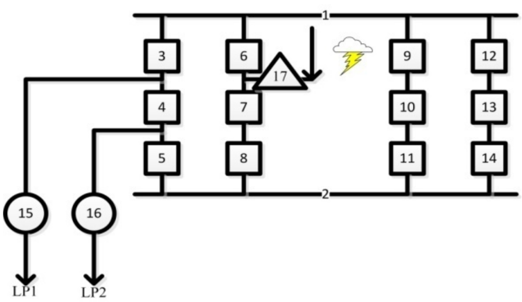


Figure 6. Graph of overvoltage in the case of presence of arrester in substation entrance

Table 6. Possibilities of Overvoltage Condition in the Case of Presence of Arrester in Substation Entrance

Lightning stroke location			Entrance arrester status	Failure rate
Inside the substation	Substation entrance	Between 50 m to 150 m from substation		
*			SC or OC	λ_{L1}
	*		SC or OC	λ_{L2}
		*	SC	0
		*	OC	$P_{L3}\lambda_{oc}$

SC and OC stand for short circuit and open circuit status of arrester respectively.

Therefore, load point reliability indices of this case are calculated using "(10)", "(11)" and "(12)".

$$\lambda_{E2} = \lambda_{L1} + \lambda_{L2} + p_{L3}\lambda_{oc} \quad (10)$$

$$U_{E2} = \lambda_{E2} r_{15} \quad (11)$$

$$r_{E2} = U_{E2} / \lambda_{E2} \quad (12)$$

c. Presence of arrester in transformer feeder (T)

1) Normal operating condition

With the help of Figure 7 minimal cut sets and load point reliability indices can be obtained.

First order: 15, 17

Second order: 1-2, 2-3, 1-5, 3-5, 3-4, 1-4

$$\lambda_{T1} = \lambda_{15} + \lambda_{sc} + \lambda_1\lambda_2(r_1 + r_2) + \lambda_2\lambda_3(r_2 + r_3) + \lambda_1\lambda_5(r_1 + r_5) + \lambda_3\lambda_5(r_3 + r_5) + \lambda_3\lambda_4(r_3 + r_4) + \lambda_1\lambda_4(r_1 + r_4) \quad (13)$$

$$U_{T1} = \lambda_{15}r_{15} + \lambda_{sc}r_{sc} + \lambda_1\lambda_2 r_1 r_2 + \lambda_2\lambda_3 r_2 r_3 + \lambda_1\lambda_5 r_1 r_5 + \lambda_3\lambda_5 r_3 r_5 + \lambda_3\lambda_4 r_3 r_4 + \lambda_1\lambda_4 r_1 r_4 \quad (14)$$

$$r_{T1} = U_{T1} / \lambda_{T1} \quad (15)$$

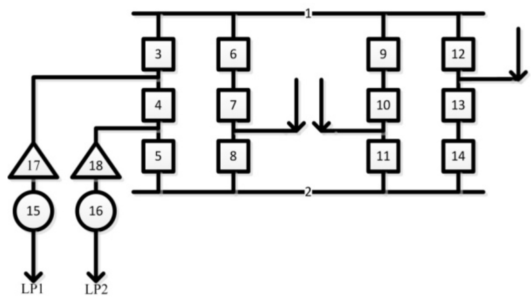


Figure 7. Graph of Normal Operating Condition in the Case of Presence of Arrester in Transformer Feeder

2) Overvoltage condition

Same as previous case all the possibilities have to be verified and then load point reliability indices can be estimated.

$$\lambda_{T2} = \lambda_{L1} + \lambda_{L2} + p_{L3}\lambda_{oc} \quad (16)$$

$$U_{T2} = \lambda_{T2} r_{15} \quad (17)$$

$$r_{T2} = U_{T2} / \lambda_{T2} \quad (18)$$

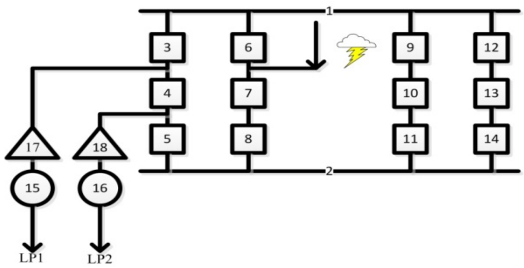


Figure 8. Graph of Overvoltage in the Case of Presence of Arrester in Transformer Feeder

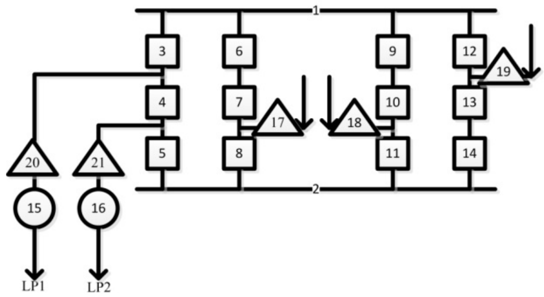


Figure 9. Graph of Normal Operating Condition in the Case of Presence of Arrester in Substation Entrance and Transformer Feeder

Table 7. Possibilities of Overvoltage Condition in the Case of Presence of Arrester in Transformer Feeder

Lightning stroke location			**Transformer arrester status**	**Failure rate**
Inside the substation	Substation entrance	Between 50 m to 150 m from substation		
*			SC or OC	λ_{L1}
	*		SC or OC	λ_{L2}
		*	SC	0
		*	OC	$P_{L3}\lambda_{oc}$

d. Presence of arrester in entrance and transformer feeder (E+T)
1) Normal operating condition
Cut sets and indexes of this case are as follows:
First order: 15, 20
Second order: 1-2, 2-3, 1-5, 3-5, 3-4, 1-4
Third order: 17-18-19

$$\lambda_{(E+T)1} = \lambda_{15} + \lambda_{sc} + \lambda_1\lambda_2(r_1 + r_2) + \lambda_2\lambda_3(r_2 + r_3)$$
$$+\lambda_1\lambda_5(r_1 + r_5) + \lambda_3\lambda_5(r_3 + r_5) + \lambda_3\lambda_4(r_3 + r_4)$$
$$+\lambda_1\lambda_4(r_1 + r_4) + \lambda_{sc}^3(3r_{sc}^3) \quad (19)$$

$$U_{(E+T)1} = \lambda_{15} r_{15} + \lambda_{sc} r_{sc} + \lambda_1 \lambda_2 r_1 r_2 + \lambda_2 \lambda_3 r_2 r_3$$
$$+ \lambda_1 \lambda_5 r_1 r_5 + \lambda_3 \lambda_5 r_3 r_5 + \lambda_3 \lambda_4 r_3 r_4 + \lambda_1 \lambda_4 r_1 r_4 + \lambda_{sc}^3 r_{sc}^3 \quad (20)$$

$$r_{(E+T)1} = U_{(E+T)1} / \lambda_{(E+T)1} \quad (21)$$

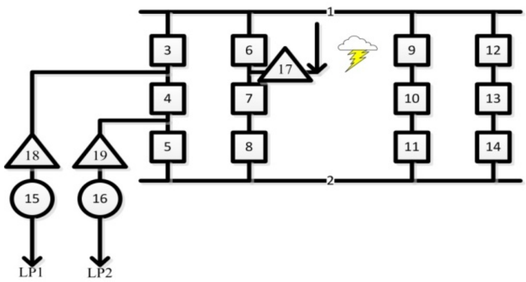


Figure 10. Graph of Overvoltage in the Case of Presence of Arrester in Substation Entrance and Transformer Feeder

2) Overvoltage condition

Owing to presence of more than one arrester in this case, the number of possibilities that have to be considered become more, that are shown in Table 8.

Owing to very small value of overvoltage duration (around few microseconds), the terms including t_{ov} can be ignored, i.e. probability of entrance and transformer arresters failure simultaneously is practically impossible. So load point reliability indices can be written as follows:

$$\lambda_{(E+T)2} = 2(p_{L1} + p_{L2})\lambda_{oc} \quad (22)$$

$$U_{(E+T)2} = \lambda_{(E+T)2} r_{15} \quad (23)$$

$$r_{(E+T)2} = U_{(E+T)2} / \lambda_{(E+T)2} \quad (24)$$

Finally after calculating the average failure rate and average unavailability of normal operating and overvoltage conditions separately, total value of each case average failure rate and average unavailability will be sum of conditions ones of each case. Consequently total average repair time is division of total average unavailability on total average failure rate.

Table 8. Possibilities of Overvoltage Condition in the Case of Presence of Arrester in Transformer Feeder

Lightning stroke location			**Arrester status**		**Failure rate**
Inside the substation	Substation entrance	Between 50 m to 150 m from substation	Entrance arrester	Transformer feeder arrester	
*			SC	SC	0
*			OC	SC	$P_{L1}\lambda_{OC}$
*			SC	OC	$P_{L1}\lambda_{OC}$
*			OC	OC	$2p_{L1}\lambda_{oc}(\lambda_{oc}t_{ov})$
	*		SC	SC	0
	*		OC	SC	$P_{L2}\lambda_{OC}$
	*		SC	OC	$P_{L2}\lambda_{OC}$
	*		OC	OC	$2P_{L2}\lambda_{oc}(\lambda_{oc}t_{ov})$
		*	SC	SC	0
		*	OC	SC	0
		*	SC	OC	0
		*	OC	OC	$2P_{L3}\lambda_{oc}(\lambda_{oc}t_{ov})$

Table 9. Reliability Data

Description	λ (fail/year)	P	r (hour)
Busbar	0.0020	-	10
Circuit Breaker	0.0050	-	48
Transformer	0.015	-	528
Arrester short circuit failure	0.0048	-	50
Arrester open circuit failure	0.0025	-	-
Annual number of lightning stroke to inside the substation due to shield wire failure	0.0020	-	-
Annual number of lightning stroke to substation entrance due to shield wire failure	0.0030	-	-
Annual number of lightning stroke to points between 50 m to 250 m from substation due to shield wire failure	0.0050	-	-
Probability of annual lightning stroke to inside the substation due to shield wire failure	-	0.0020	-
Probability of annual lightning stroke to substation entrance due to shield wire failure	-	0.0030	-
Probability of annual lightning stroke to points between 50 m to 250 m from substation due to shield wire failure	-	0.0050	-

4.2. Numerical Analysis Discussion

Via reliability data given in Table 9, load point reliability indices of the different cases for each condition and sum of conditions are shown in Figure 11-13.

According to reliability evaluation results, during normal operating condition of substation, reliability in the case of absence of arrester is in its best manner, since there is no possibility of short circuit failure and in this condition the case of presence of arresters in entrance and transformer feeder has the lowest reliability. Vice versa during overvoltage, absence of arrester reduces the reliability intensely and enhance the unavailability. Adding arrester improves reliability but to get expected reliability and security of substation, both of entrance and transformer surge arresters should collaborate together.

In the configuration of all substations, the first order cut set has dominant impact on reliability indices. Mostly, transformers for the reason of direct connection to load point forms first cut set. Presence of arrester close to transformer forms first cut set too that with transformer are highly weighted on reliability indices.

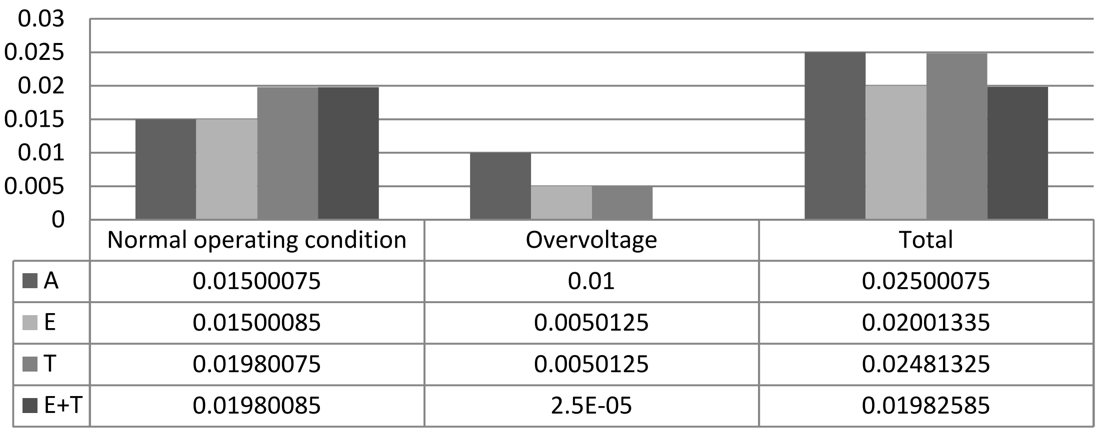
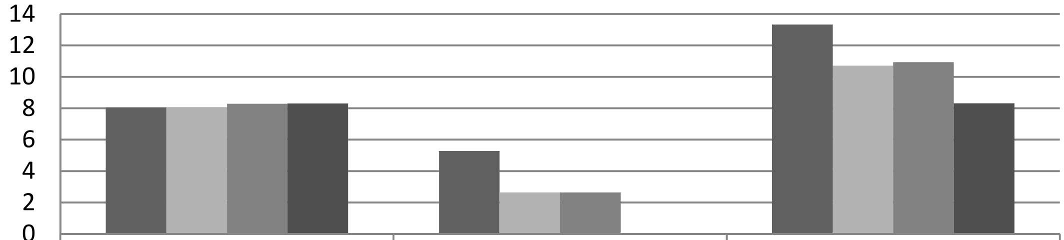


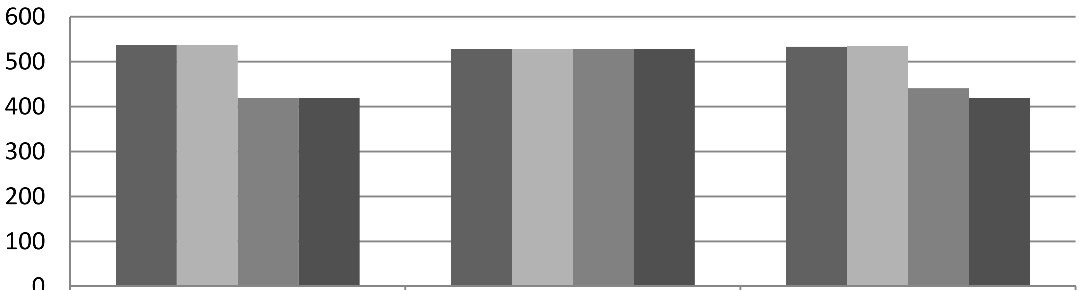
Figure 11. Average Failure Rate of Load Point

It should be noted that annual number of lightning stroke or Probability of annual lightning stroke is very effective on reliability indices. The smaller the values of annual number of lightning stroke or Probability of annual lightning stroke is, the lower role of arrester in the system and lower reliability indices of the case of absence of arrester than other cases.



	Normal operating condition	Overvoltage	Total
A	8.05	5.28	13.33
E	8.063824	2.6466	10.710424
T	8.29	2.6466	10.9366
E+T	8.303824	0.0132	8.317024

Figure 12. Average Unavailability of Load Point



	Normal operating condition	Overvoltage	Total
A	536.6396	528	533.1839
E	537.5578	528	535.164
T	418.6709	528	440.7563
E+T	419.367	528	419.504

Figure 13. Average Outage Time of Load Point

5. Conclusion

Occurring overvoltage such as lightning surge in the power system and intruding the transient waves into the substations oblige designers to consider surge arrester for substations. Short circuit failure during normal operating condition and open circuit failure during overvoltage may result in load interruption. This paper by employing EMTP simulation and reliability assessment evaluates arresters failure impact on substation. First a brief description of elements models such as lightning surge, transmission lines, towers and equipment of the selected substation that have been take into account is presented. Then various scenarios of surge arresters locations and lightning stroke positions are analyzed.

After simulating the related substation and finding the scenarios that can be harmful for that, by means of cut set approach, load point reliability indices for normal operating and overvoltage condition are calculated. Eventually reliability assessment proves the best case in comparison with other cases that were evaluated is presence of arresters in substation entrance and in transformer feeder. Failure of arresters in vital locations which were discussed leads to reliability drop.

EMTP simulation shows just presence of arresters in entrance and in transformer feeder is sufficient to protect the substation against any kind of overvoltage which may occur in network. Adding additional arresters to substation e.g. on the busbar or near the breaker however, can alleviate overvoltage but increases the failure rate and unavailability during normal operating condition and reduce the reliability totally.

Annual number of lightning stroke or Probability of annual lightning stroke has dominant effect on reliability indices in overvoltage condition. if these values become too small, the case of absence of arrester tends to be the best case than other cases.

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