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# Line Surge Arrester Application on the Quadruple Circuit Transmission Line

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*Abstract* - **This paper presents results of the study dealing with the application of line surge arresters on the quadruple circuit transmission line. Considered transmission line consists of two 275 kV circuits and two 132 kV circuits. Line surge arrester with external gap is installed on the 132 kV circuit. Different arrester installation configuration are studied and compared. Line surge arrester installation strategy is presented.**

*Index Terms* - **Backflashover, Double circuit outage, Lightning performance, Line surge arrester, Shielding failure**

## I. INTRODUCTION

The use of line surge arresters to improve transmission line lightning performance or to avoid double circuit outages has increased over the last decade. Many line surge arresters are in service today and substantial service experience has been accumulated [1], [2], [3], [4]. The majority of line surge arresters are installed on lines having nominal voltages between 44 kV and 138 kV, but the application of this type of technology has been extended to the distribution lines and also to the transmission lines up to 500 kV.

Tenaga Nasional Berhad, Malaysian electric power utility is using line surge arrester for the transmission line lightning performance improvement from 1995. Line surge arresters with an external gap are installed on 132 kV lines, mainly to reduce double circuit outage rate.

Experience with the installed line surge arresters is positive; surge arresters are performing correctly and there is evidence of the transmission line lightning performance improvement.

Line surge arresters are normally installed on all phase conductors of one circuit of the double circuit line. Arresters are installed on all towers of the considered 132 kV line. With this arrester installation configuration, double circuit outages are eliminated, but there exists possibility to have flashovers on the circuit without arresters.

Based on the positive experience with the line surge arresters on 132 kV double circuit lines, it was decided to extend line surge arrester application to the quadruple circuit lines: 2 x 275 kV and 2 x 132 kV. The lower voltage (132 kV) circuits of the quadruple line have lower line insulation critical flashover voltage, which means that the majority of the backflashovers will happen on the 132 kV circuits (thanks to this "natural" line insulation differential).

Application of the line surge arresters on 132 kV circuits only was studied. These arresters are cheaper than the arresters for 275 kV circuits. By the application of the line arresters on 132 kV circuits only, line overall lightning performance is improved.

Several line surge arrester installation configurations are studied. The main goal was to reduce line double circuit outage rate, but also to improve line total lightning performance.

Taking into account that the considered line has a different footing resistance along the line route, tower footing resistance value was also varied.

Line surge arrester with an external series gap was selected. This type of the arrester is presently used in Tenaga Nasional Berhad transmission network.

## II. QUADRUPLE CIRCUIT TRANSMISSION LINE

Quadruple circuit transmission line Balakong-Bandar Tun Razak, being commissioned in 1992, consists of two 275 kV circuits and two 132 kV circuits (Fig. 1). Route length is 10.6 km and number of towers is 37. Average line span is 300 m. Line is operating in the region with an average ground flash density of 10-20 strokes/km$^2$/year.

Two shield wires provide a negative shielding angle. Metal construction transmission towers are 52 m high. Line conductor data is given in Annex (Table A.I).

After the commissioning, this line has experienced a several double circuits outages on 132 kV circuits. It was decided to install line surge arresters on all phase conductors and on all towers of one 132 kV circuit in order to completely eliminate 132 kV double circuit flashovers. Polymer housed line surge with an external gap (Fig. 2) are installed in 2000.

The main goal of this study was to analyse different line surge arrester installation configurations in order to optimise application of this technology to the existing and to the future quadruple transmission lines.

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Fig.1 - Quadruple circuit transmission line
2 x 275 kV (top) and 2 x 132 kV (bottom)

Fig.2 - Line surge arrester with an external gap installed on one 132 kV circuit

## III. MODELLING, SIMULATION TOOL AND STUDY DATA

All computer simulations are performed using *sigma slp* simulation software tool [5]. *Sigma slp* is PC Windows based software, which has been specially developed to enable quick and easy determination of transmission line lightning performance. A short description of the models implemented into software and the representations used in this study follows.

### *A. Electromagnetic transients*

Electromagnetic transients computation algorithm is based on the complete system decomposition [6]. Transients on the conductors (phase conductors and ground wires) are performed separately using a multiphase lattice diagram method. A phase domain transmission line model is used. Transients on the towers are computed using numerical integration techniques. Interconnection between conductors and towers (connection of ground wires to towers, line insulation flashovers, line surge arresters when used) is performed in each time step using Thevenin multiphase equivalents. Transients on the line tower footing system are also computed separately, and the interconnection to the tower is done in each time step.

### *B. Electrogeometric model*

The software automatically implements a three-dimensional electrogeometric model. Line span is divided into short sections (10 to 15 m each), in order to accept lightning stroke to the ground wires or to the phase conductors along the span. A total number of 20 to 30 thousand strokes are used in the electrogeometric simulations. Following striking distances are used:

- The striking distance to a conductor [7]

$$r_c = 10 I^{0,65} \qquad (1)$$

- The striking distance to earth [8]

$$r_e = 5,5 I^{0,65} \qquad (2)$$

- The striking distance to tower top

$$r_T = 1,05\ r_c \qquad (3)$$

I(kA) - Lightning stroke current

A two-line CIGRE stroke distribution [7] is modified to represent stroke distribution to a flat ground - Table I.

TABLE I

TWO-LINE STROKE DISTRIBUTION TO FLAT GROUND

| Parameter | Shielding failure range [I < 15.9 kA] | Backflashover Range [I > 15.9 KA] |
|---|---|---|
| $I_M$(kA) | 48.4 | 26.4 |
| σ | 1.33 | 0.605 |

$I_M$(kA) - median value of the stroke current
σ - logarithmic standard deviation

In the electrogeometric modelling, it was taken that the downward leaders are approaching under randomly varied angle. Corresponding probability density function has the following form:

$$f(\Psi) = \frac{2}{\pi}\cos^2\Psi \tag{4}$$

Ψ - downward leader approaching angle to the vertical axis

*C. Tower footing resistance model*

The software provides a different tower footing resistance models:

- constant resistance model
- soil ionisation model [7]
- frequency dependant counterpoise model [9]

In this study, a soil ionisation model is used. The tower footing impulse resistance is described by the following equations:

$$R_i = \frac{R_T}{\sqrt{1+\left(\frac{I}{I_g}\right)}} \tag{5}$$

$$I_g = \frac{E_g \rho}{2\pi R_{lc}^2} \tag{6}$$

$R_T$ - low current tower footing resistance (Ω)
$R_i$ - tower footing impulse resistance (Ω)
ρ - Soil resistivity (Ωm)
I - impulse current (kA)
$I_g$ - soil ionisation limit current (kA)
$E_g$ - soil ionisation critical electric field (kV/m)
[$E_g$ = 400 (kV/m)]

The tower footing low current resistance was varied between 10 Ω and 40 Ω, while the ratio between the soil resistivity and the tower low current resistance was kept constant, being 50.

*D. Line insulation flashover model*

The leader propagation model [7] is used to represent line insulation flashovers:

$$v_l = 170\, d \left[\frac{u(t)}{d - l_l} - E_0\right] e^{0{,}0015 \frac{u(t)}{d}} \tag{7}$$

$v_l$ - Leader velocity (m/s)
d - Gap distance (m)
$l_l$ - Leader length (m)
u(t) - Applied voltage (kV)
$E_0$ = 520 (kV/m)

Critical flashover voltage ($U_{50\%}$) of 275 kV circuits was 1120 kV and this value for 132 kV was 880 kV.

Flashover voltage of all line insulators in the simulated section is randomly varied, according to the normal distribution. Standard deviation for the line insulation flashover voltage was 3 %.

*E. The power frequency voltage*

Effect of the power frequency voltage on the line lighnting performance is also taken into account. Initial power frequency voltage is randomly varied, according to the following expression:

$$\varphi_A = RND \cdot 360^{\circ} \tag{8}$$

$\varphi_A$ - Phase conductor A voltage angle (°)
RND - Uniform distribution random number
[between 0 and 1]

Phase angles for the remaining conductors are obtained by the introduction of the corresponding phase shift (± 120°).

*F. Tower model*

Transmission line tower model, used in all simulations is presented in Fig. 3. Section of the tower from the bottom crossarm to the ground is represented as propagation element, which is defined by the surge impedance $Z_T$ and the propagation length $l_{prop}$. Wave propagation speed on the tower was taken to be equal to the velocity of light.

Sections on the tower top [between tower top and top crossarm and between crossarms] are modelled as inductance branches. Branch inductance is determined according to the section length, tower surge impedance and the propagation velocity. In the parallel to the inductance branches a damping resistors are introduced.

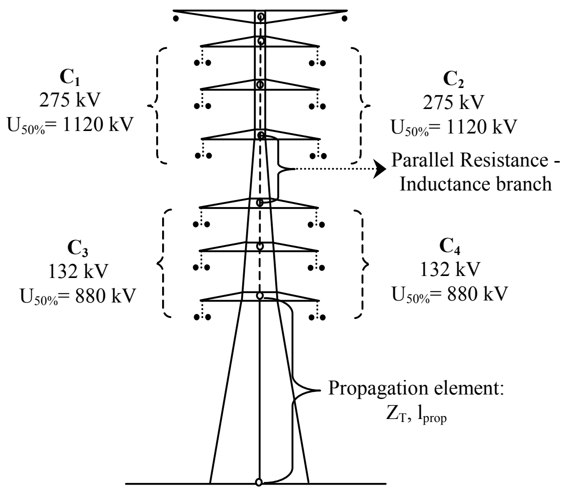


Figure 3 - Studied quadruple circuit transmission line (Tower representation)

*G. Line surge arrester*

Polymer housed line surge arrester with an external series gap is used for the line lightning performance improvement. Used arrester has the following characteristics:

| | |
|---|---|
| Rated voltage: | 120 kV |
| Series gap spacing: | 650 mm |
| IEC Line discharge class: | II |
| Critical flashover voltage: | 620 kV |

The voltage-time curve of the arresters is modelled using the equal area law [7]. After operation, arresters are modelled by its discharge voltage curve. A series inductance is added to model discharge voltage change with the surge steepness.

*H. Simulated section of line*

The simulated section of the line consists of several towers (up to 20 in the software). At the ends of the simulation sections, coupling matrices are added to avoid surge reflections. Each span in the simulation section is divided into short sections (10 m to 15 m), in order to accept strokes along the span and to connect corona branches.

*J. Corona*

The influence of the corona is modelled by the capacitance branches, which are connected between conductors and ground (coupling under corona is neglected). Transients on the capacitance branches representing corona are also treated separately. The interconnections with the system of the conductors are also done in each time step using Thevenin equivalents.

## IV. LINE LIGHTNING PERFORMANCE

Line lightning performance is first determined for the line without arresters. Then, several arrester installation configurations are studied, taking into account that the maximum number of the arresters to be used is less or equal to three. Arrester installation configuration on 132 kV circuits is considered only. Each tower in the analysed section of the line has the same arrester installation configuration.

A total number of 2000 electromagnetic transients statistical simulations are performed for each studied case (different tower footing resistance or arrester installation). All presented results are for a ground flash density of 20 strokes/km$^2$/year.

Lighting performance of the line without line surge arresters is presented in Table II (per circuit flashovers). As expected, the majority of the flashovers happen on 132 kV circuits. Line lightning performance strongly depends on the tower footing resistance. For the tower footing resistance less than 10 Ω, zero flashover rate is obtained (line is equipped with two shield wires with a negative shielding angle).

In Table III, line total, single, double and triple line flashover rate is presented (no quadruple simultaneous flashovers).

Number of double circuit flashovers depends on the tower footing resistance, and may reach value of 35 % of the line total flashover rate, for the tower footing resistance of 40 Ω. Number of the triple circuit flashovers (simultaneous flashovers on two 132 kV circuit and on one 275 kV) is very low.

Results of the simulation for the different line arrester installation configuration are presented in Tables IV and V. Arrester installation configuration is graphically indicated in the corresponding tables: empty - white circle - no arrester installed; black circle - arrester installed.

Table IV presents line total flashover rate (data for line without line arresters is also given for the comparison).

A substantial improvement in the line total flashover rate is obtained by the installation of line arresters on the two bottom conductors of 132 kV circuits. These two conductors have the lowest coupling factor with the ground wires. It is interesting to note that this, two arrester configuration gives better total flashover rate than the three arresters installed on the all phase conductors of one 132 kV circuit.

TABLE II
FLASHOVER RATE FOR DIFFERENT CIRCUTS WITHOUT LINE SURGE ARRESTERS
[Flashovers/100 km/year]

| $R_T$ (Ω) | $C_1$ [275] | $C_2$ [275] | $C_3$ [132] | $C_4$ [132] |
|---|---|---|---|---|
| 10 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0.78 | 2.14 |
| 20 | 0 | 0 | 5.66 | 4.88 |
| 25 | 0 | 0.19 | 12.69 | 10.92 |
| 30 | 0.19 | 0.39 | 20.69 | 20.69 |
| 35 | 0.19 | 0.58 | 29.67 | 33.58 |
| 40 | 0.19 | 0.19 | 42.55 | 46.85 |

TABLE III
LINE TOTAL AND MULTI CIRCUIT FLASHOVER RATE
WITHOUT LINE SURGE ARRESTERS
[Flashovers/100 km/year]

| $R_T$ (Ω) | Total | Single | Double | Triple |
|---|---|---|---|---|
| 10 | 0 | 0 | 0 | 0 |
| 15 | 2.93 | 2.93 | 0 | 0 |
| 20 | 8.39 | 6.24 | 2.14 | 0 |
| 25 | 18.35 | 13.08 | 5.07 | 0.19 |
| 30 | 32.60 | 23.81 | 8.19 | 0.58 |
| 35 | 49.26 | 32.41 | 14.64 | 0.78 |
| 40 | 65.64 | 41.98 | 22.84 | 0.78 |

The best improvement in the line total flashover rate is obtained by the installation of the arrester on the bottom conductors of both 132 kV circuit and on the one top conductor of one 132 kV circuit (the best three arrester installation configuration).

When line surge arresters are installed on all phase conductors of one 132 kV circuit, double circuit flashover are completely eliminated (actual installation on the considered transmission line). But, it is to note that with this arrester installation configuration line total flashover rate remains high.

Arrester installation configuration with the arresters on the bottom conductors of both 132 kV circuits and on the one top conductor of one 132 kV circuit is very attractive, because this configuration substantially reduce line total flashover rate, reducing in the same time line double circuit flashover rate. With this arrester installation configuration coupling between 132 kV circuits conductors is substantially improved. This installation configuration will be used in the future for the existing and for the new quadruple circuit transmission lines in Tenaga Nasional Berhad transmission network.

TABLE IV
LINE TOTAL FLASHOVER RATE
DIFFERENT ARRESTER INSTALLATION CONFIGURATIONS
[Flashovers/100 km/year]

| $R_T$ (Ω) | ○ ○<br>○ ○<br>○ ○<br>○ ○<br>○ ○<br>○ ○ | ○ ○<br>○ ○<br>○ ○<br>○ ○<br>○ ○<br>● ● | ○ ○<br>○ ○<br>○ ○<br>● ○<br>● ○<br>● ○ | ○ ○<br>○ ○<br>○ ○<br>● ○<br>○ ○<br>● ● |
|---|---|---|---|---|
| 10 | 0 | 0 | 0 | 0 |
| 15 | 2.93 | 0 | 0.19 | 0 |
| 20 | 8.39 | 0.78 | 2.14 | 0 |
| 25 | 18.35 | 2.53 | 6.24 | 0.58 |
| 30 | 32.60 | 5.66 | 9.37 | 0.97 |
| 35 | 47.83 | 8.78 | 15.62 | 3.12 |
| 40 | 65.64 | 13.08 | 23.62 | 3.89 |

○ - Without LSA

● - LSA Installed

TABLE V
LINE DOUBLE CIRCUIT FLASHOVER RATE
DIFFERENT ARRESTER INSTALLATION CONFIGURATIONS
[Flashovers/100 km/year]

| $R_T$ (Ω) | ○ ○<br>○ ○<br>○ ○<br>○ ○<br>○ ○<br>○ ○ | ○ ○<br>○ ○<br>○ ○<br>○ ○<br>○ ○<br>● ● | ○ ○<br>○ ○<br>○ ○<br>● ○<br>● ○<br>● ○ | ○ ○<br>○ ○<br>○ ○<br>● ○<br>○ ○<br>● ● |
|---|---|---|---|---|
| 10 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 |
| 20 | 2.14 | 0 | 0 | 0 |
| 25 | 5.07 | 0.19 | 0 | 0 |
| 30 | 8.19 | 0 | 0 | 0 |
| 35 | 14.64 | 0.58 | 0 | 0.19 (*) |
| 40 | 22.84 | 1.17 | 0 | 0.39 (*) |

○ - Without LSA　　　(*) Simultaneous Flashovers on $C_2$ and $C_4$

● - LSA Installed

## V. SURGE ARRESTER CURRENTS

Surge arrester currents are computed for a few ‘single stroke’ cases and statistically. In Fig. 4 surge arrester current shapes are presented for the following single stroke case:

*Configuration*: Given in last column of Table IV (V).
*Stroke data*: Current peak $I = 110$ kA
Front time $t_f = 4$ μs
Tail time $t_t = 75$ μs
*Footing resistance:* $R_T = 30$ Ω
$\rho = 1500$ Ωm
*Stroke location*: Tower top

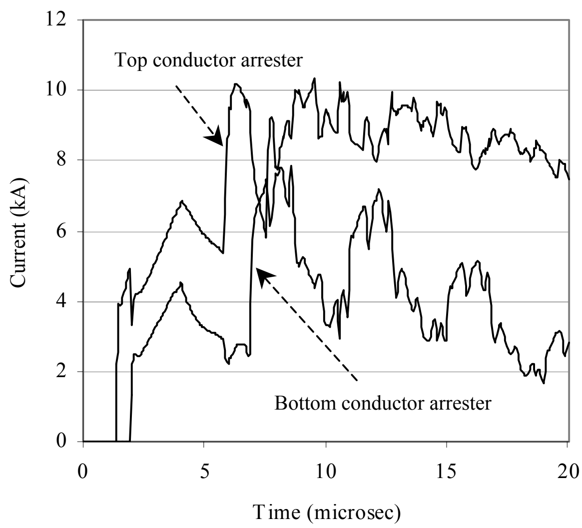


Figure 4 - Surge arrester current shapes
(Top and bottom arresters currents)

Line surge arrester installed on the bottom conductor takes higher current than that one on to top conductor. The reason for this is the difference in the coupling factors (bottom conductor has lower coupling factor with the ground wires).

The cumulative statistical distributions of line surge arrester currents for different tower footing resistance are presented in Table VI. Arrester installation configuration is the same as in the previous single stroke case. Presented distributions are based on 2000 statistical simulations for each value of the tower footing resistance. The low probability regions are given.

According to the presented results, we can see that line surge arresters are not heavily stressed. The main reason for that is the fact that the line in question is equipped with a two shield wires, which help to divert stroke current.

Arrester currents depend on the tower footing resistance. Lower is tower footing resistance lower are surge arrester currents. For the tower footing resistance of 10 Ω, arrester are operating in 1 % cases only, with a very low current peaks.

## VI. CONCLUSIONS

1. Lightning performance of the quadruple circuit transmission line, having different voltage levels, can be improved by the installation of the line surge arresters on the lower voltage level circuits only. This enables line lightning performance improvement using cheaper arresters.
2. Lower voltage level circuits have lower critical flashover voltage, which means that the majority of the backflashovers will happen on these circuits.
3. Installing line surge arresters on the lower voltage circuits will prevent flashovers on these circuits, but also improve coupling between lower and higher voltage circuits. In addition, line surge arresters divert stroke current along the phase conductors, reducing in this way the current through the tower footing resistance.
4. Arrester installation on the all phase conductors of one 132 kV circuit of the considered quadruple transmission line, eliminates double circuit flashover, but line total flashover rate remains high.
5. Three arrester configuration, with the arresters installed on the bottom conductors of 132 kV circuits and on the top conductor of the one 132 kV circuits substantially reduces line total and double flashover rate.
6. Thanks to the fact that the analysed quadruple transmission line has a two shield wires, line arrester are not heavily stressed by the impulse currents. Shield wires provide a negative shielding angle, which minimise probability for the shielding failures.

Table VI
CUMULATIVE FREQUENCY DISTRIBUTIONS OF THE ARRESTER CURRENTS
[Low probability range]

| Probability (%) | $R_T = 10$ (Ω) | $R_T = 20$ (Ω) | $R_T = 30$ (Ω) | $R_T = 40$ (Ω) |
|---|---|---|---|---|
| 0.5 | 3.3 | 8.3 | 9.9 | 10.7 |
| 1 | 2.0 | 5.6 | 8.3 | 10.0 |
| 2 | 0 | 3.9 | 6.2 | 7.7 |
| 5 | 0 | 3.1 | 4.1 | 5.1 |
| 10 | 0 | 0 | 3.0 | 3.6 |

## VII. ANNEX

Line conductor data is given in Table A.I.

Table A.I
LINE CONDUCTOR DATA

| No | Circuit | x (m) | y(m) | r (mm) | Sag (m) |
|---|---|---|---|---|---|
| 1 | $C_1$ | -6 | 44.83 | 11.29 (*) | 10 |
| 2 | $C_1$ | -6 | 38.13 | 11.29 | 10 |
| 3 | $C_1$ | -6 | 31.43 | 11.29 | 10 |
| 4 | $C_2$ | 6 | 44.83 | 11.29 (*) | 10 |
| 5 | $C_2$ | 6 | 38.13 | 11.29 | 10 |
| 6 | $C_2$ | 6 | 31.43 | 11.29 | 10 |
| 7 | $C_3$ | -6 | 23.2 | 9.77 (*) | 10 |
| 8 | $C_3$ | -6 | 18.55 | 9.77 | 10 |
| 9 | $C_3$ | -6.3 | 13.87 | 9.77 | 10 |
| 10 | $C_4$ | 6 | 23.2 | 9.77 (*) | 10 |
| 11 | $C_4$ | 6 | 18.55 | 9.77 | 10 |
| 12 | $C_4$ | 6.3 | 13.87 | 9.77 | 10 |
| 13 | $GW_1$ | -8.9 | 51.26 | 4.37 | 7 |
| 14 | $GW_2$ | 8.9 | 51.26 | 4.37 | 7 |

(*) Twin conductor bundle: sub-conductor radius

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## IX. BIOGRAPHIES

**Yusof Abdul Wahab** was born in Kuala Lumpur, Malaysia on 13th October 1951. He graduated from University of Southampton, United Kingdom in Electrical Engineering in 1974. He has worked for Tenaga Nasional Berhad (TNB), the Power Utility of Malaysia from 1974 until now in Transmission and Distribution Divisions. His field of experience includes Transmission substation design and special field of interest includes Gas Insulated Substation.

**Z Z Abidin** was born in Malaysia. He graduated in Electrical and Electronic Engineering from the University of Glasgow, Scotland. He has worked for Tenaga Nasional Berhad, the Power Utility Company in Malaysia, from 1980 till now. Employment experience includes Rural Electrification Project, Transmission Line Project Management and Transmission Maintenance.

**Salih Sadovic** was born in Trebinje, Bosnia-Herzegovina in 1947. He received the Diploma engineering degree from the University of Sarajevo (Bosnia-Herzegovina) and Master and Doctor of Science degrees from the University of Zagreb (Croatia) in 1973, 1977 and 1981 respectively. Since 1973 Dr Sadovic was at the University of Sarajevo, where he was Professor of Electric Power Engineering. He was Dean and Vice Dean of the Electrical Engineering Department.

In 1993 and 1994 he worked at Electricite de France - Research and Development Department. From 1994 he is a consultant. His research interests include overvoltages and insulation co-ordination, power systems analysis, numerical field computations and computer applications in power engineering.