

Lightning Protection Analysis of Light Rail Transit DC Overhead Contact System

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Abstract —At present there are no industry standards or recommended guidelines for the light rail transit dc Overhead Contact System (OCS) design that deal with lightning protection. Derivations of lightning intensity and lightning stroke surge energy are provided. Discussion of lightning stroke to OCS components and consequently flashing over to ground is included in this paper. Analysis of surge overvoltage at the junction of OCS to underground positive supplementary cable is established. Lightning protection analysis presented in this paper clarifies design myths and guesswork of applying surge arresters due to over concerns of lightning protection. Recommendation to apply dc surge arresters to protect OCS from lightning stroke is included.

Index Terms — Isokeraunic level, Overhead Contact System (OCS), lightning flash, lightning stroke, lightning intensity, surge arrester, supplementary cable.

I. INTRODUCTION

This paper attempts to provide an engineering analysis of lightning strike to the light rail transit (LRT) dc traction power system components. This includes, overhead contact system (OCS), the running rails, OCS supporting structure, metallic poles, messenger wire, underground positive supplementary conductors, traction power substations, and vehicles anywhere on the tracks.

Lightning waveform parameters should be known before quantitative cause and effect; an engineering analysis of lightning protection can then be performed. It appears that there is a mismatch between the actual number of lightning strikes and specificity of the lightning parameters required in performing lightning protection analysis for a rail transit system. At present there is no data for the lightning effects and design experience available from the operating transit properties. Today's operational lightning location systems (LLS) [1], ongoing research, and scientific ability to measure lightning parameters can avoid guesswork in rail transit system lightning protection design. From a cause and effect standpoint, the maximum rate-of-rise, the peak current, and the wave front rise-time are associated with determining the maximum voltage that will be seen on the OCS system subjected to unpredictable threat of a direct or nearby ground lightning discharge. The probability of threat of lightning

strike is relatively more when the rail transit system is located in a high isokeraunic level area. [2].

To establish lightning protection design measures, the derivation of lightning intensity and lightning stroke surge energy is established based upon the typical available lightning data. There are equal chances of lightning strike hitting any of the system components due to their proximity, and thus flashover is certain if lightning strikes the OCS messenger wires since poles and OCS supporting members are practically grounded. Flashover appears to drain large amount of lightning surge energy to ground and the remainder of the surge energy can be relieved by the application of dc surge arresters at appropriate locations.

When considering lightning protection for OCS, numerous questions arise, such as:

- 1) Will dc surge arrester handle surge energy if a lightning flash directly hits the OCS wire near the arrester location?
- 2) If a lightning flash directly hits the OCS wire in the middle of two traction power substations, what will be the energy discharged through the surge arresters at feeder poles?
- 3) Is there a need to apply dc surge arresters at the mid-point of two adjacent substations spaced approximately 1 1/2 miles apart to enhance the lightning protection of the LRT system?
- 4) Do we need to apply surge arresters at the connection points of underground dc supplementary feeder cable to OCS contact wire located approximately every 400 feet, where overhead messenger wire design is not possible in downtown areas due to aesthetics and other restrictions of height of the messenger wires?
- 5) Should there be shield/ground wire above the messenger to enhance lightning protection?

Responses to above questions are discussed in this paper.

Lightning may be of concern when the LRT system is in a relatively high isokeraunic area. Isokeraunic area map of the world can be seen in reference [9]. In addition, dealing with a transit system involving the general public and, more importantly, the traffic havoc due to interruption of system caused by lightning is LRT design concern. Thus an appropriate lightning protection system consisting of MOV dc surge arresters should be installed.

To minimize the effect of lightning surge voltages to a typical LRT traction power system equipment, application recommendation of surge arresters is included.

II. LIGHTNING INTENSITY

Lightning intensity within a specific area is generally based upon the ground flash density, N_g , in flashes per km^2/year . At present, this data is not available in the United States and thus, lightning intensity must be based upon the isokeraunic level, or the number of thunderstorms per year, T_d . The value of N_g may be approximated by using the following empirical expression [2][3]. With more research data available in the future such an expression may change.

$$N_g = 0.04 T_d^{1.25} \quad (1)$$

For example consider the Houston area light rail transit (LRT) where T_d is in the order of 40-60 [3]. Using expression (1) and T_d of 60, the calculated value of N_g will be near 6.68. It is noted that the exponent value of 1.25 in expression (1) is somewhat uncertain, for some published literature indicates this value to be 1.35. However, 1.25 has been accepted by the committee responsible for the development of the standard [2] and thus, for this example, OCS lightning protection analysis will be based upon the value of N_g to be around 6.68.

This calculated number for N_g provides some measure of likelihood of lightning strike to ground in the Houston area. The actual number of lightning flashes/year, N_{OCS} , that may strike the light rail OCS or nearby ground inducing direct or indirect lightning surge waves, may be calculated by using the following expression:

$$N_{OCS} = WLN_g \quad (2)$$

Where:

L = length of LRT system in kilometers

W = Width of area covering LRT tracks in kilometers

Assuming a double track LRT system with width near 0.015 kilometer and N_g of 6.68, by expression (2), calculated value of N_{OCS} will be approximately $L/10$.

Thus in the above example for an LRT system with 10 km length, the calculated number of lightning flashes per year (N_{OCS}) that may strike the LRT system is unity. The expected single lightning flash per year may not be a direct hit to the OCS system. In addition, the expected single lightning flash may or may not be of concern, depending upon the severity

and energy associated with the lightning stroke (surge) contained in the flash.

A. Lightning Stroke Terminology

Perhaps it is best to clarify the terminology. Reference [5] makes a distinction between the traditionally used term “stroke” and a more precise reference to the term, “flash”. A flash describes the entire electrical discharge to the stricken object. Stroke, on the other hand, describes only the high-current components of a flash. Because of the observed multiplicity of strokes, the relationship between the terms “flash” and “stroke” is that there can be many strokes in a single flash. Research into flash characteristics indicates that 55 percent of all flashes contain multiple strokes, with an average value of three strokes [5]. This information is important because of the differences in wave shape of the successive strokes. The term “flashover” is described as an electrical discharge completed from an energized conductor to a grounded support structure, which will be OCS poles in case of an LRT system.

B. Lightning Stroke Magnitude

Research on the stroke current peak amplitude reported that the mean value of first stroke is near 31 kA, with a 95 percent probability of the stroke magnitude being between 10 and 100 kA [5]. The first stroke wave shape mean value just before the current peak has been reported to be near 24.3 kA/ μs , which is helpful in understanding the impulse voltages that can occur for discharges through inductances. It is necessary to indicate that although the average value of the peak magnitude of the subsequent stroke(s) is generally less than the first stroke, the wave front(s) of the subsequent stroke(s) are typically faster. The average value is near 39.9 kA/ μs , although values in excess of 70 kA/ μs have been reported. The above mentioned stroke parameters relate to the flash itself and much of the data was obtained from mountaintop observatories. It is also reported that 60 percent of the direct flashes hit the tower where they would flashover to the ground and the remainder hit on the spans between the towers.

The above listed current lightning waves develop very high corresponding voltage waves based upon their relationship provided by the following expressions [6][7]:

$$E = IZ \quad (3)$$

$$di/dt = dv/dt (1/Z) \quad (4)$$

Where:

E = surge voltage

I = surge current

Z = surge impedance

di/dt = rate-of-rise of surge current

Consideration must be given to some modification of the flash characteristics striking an LRT contact wire system, especially when tracks may be surrounded by urban development. Any high-rise buildings, including the trees and street light poles that are taller than the OCS poles, will provide some degree of lightning flash shielding to the OCS system. However, since there is no measured research data specifically for the LRT system, the conservative approach is to use the data available for the transmission towers for the LRT system.

C. Lightning Stroke Induced Overvoltage

Lightning overvoltages are also possible due to electric and magnetic fields induced from nearby lightning, often referred to as indirect or induced strikes. For transmission lines, peak overvoltages induced by first strokes varied between +150 kV and -40 kV, the mean being 23 kV. The mean rise time for these voltage surges was 6 μ s. This provides rate of rise of the voltage wave to be approximately 4 kV/ μ s. The study further revealed that induced overvoltages caused by subsequent lightning strokes had 11 kV peaks, with a mean rise time of 4 μ s. This provides a rate of rise of the voltage wave to be approximately 3 kV/ μ s, which is much lower than the values reported for the direct lightning flash hitting the transmission lines. Such lightning wave parameters may be used for LRT system design and engineering analysis of lightning protection, which is the main theme of this paper.

III. LIGHTNING STROKE - OCS FLASHOVER

This discussion is intended to establish the lightning overvoltage intensity to the OCS components, especially the contact wire, which is generally protected by dc surge arresters. The various components of the OCS, including messenger wire, contact wire, and supporting structure (which consists of metallic poles, cross-arms, and running rails), are relatively close to each other. There are equal chances that the lightning strike may hit any of the above-described OCS components.

The messenger wire, cross-arms, and grounded metallic poles may provide some measure of shielding of direct lightning strike to the OCS contact wire. In rare circumstances, if the lightning strikes directly to the OCS wire, flashover is almost certain since the insulated air gaps and clearances from the grounded metallic components including the poles is relatively low with wet and dry

flashover values near 20 kV to 35 kV peak respectively. Lightning strike energy after the flashover at the OCS pole will go to ground by surge impedance magnitude of the grounding path of the poles.

After the flashover, the maximum voltage expected at the OCS contact wire would not be more than 35 kV peak. The time to flashover, the energy contained in the remaining surge wave at the OCS, and its propagation away from the point of strike will depend upon the rate-of-rise of the incoming surge waves of the lightning flash strokes. As indicated earlier, 60 percent of the strokes may strike the OCS poles and the remainder at mid-spans of poles spaced approximately every 100 feet to 150 feet apart.

It appears that the maximum distance that a lightning surge will need to travel before hitting the grounded pole for flashover phenomenon is around 75 feet, which in terms of the surge wave propagation time is very small (0.075 μ s). Without the application of dc surge arrester at each OCS pole, the metallic grounded OCS poles will provide adequate path to the lightning strokes with peak voltages exceeding 35 kV peak. This OCS poles flashover to ground will cease automatically once the OCS surge voltage falls below 35 kV. The flashover may occur again if there are repeated lightning strokes in a particular flash.

If the flashover occurs near the dc feeder poles with dc surge arresters, the dc surge arrester may also start discharging during the pole flashing. It is also apparent that as the propagation time of the surge to adjacent feeder pole towards the next substation is small, the surge arrester on adjacent substation will also start conducting. In addition, the surge wave will also propagate via an underground feeder cable to the dc switchgear with a reduced surge magnitude indicated by expression (5) of reference [7]. Thus, surge arresters applied at the dc feeder breakers will reduce the effect of surge propagation on feeder cables and the substation equipment.

In a rare situation for a LRT system in a high isokeraunic area, if the pole flashover for some reason involves the running rails, then the surge may propagate to the substation negative bus box by negative underground dc feeders. Thus, it is recommended that surge arresters should also be applied at the dc negative bus box.

In case of severe lightning stroke, a concern of damage to the surge arrester rises due to its limited surge energy handling capability. However, it appears, that for such a severe lightning stroke, flashover across the outer surface of the surge arrester may occur due to its short length. Such flashovers will drain the surge energy to ground leaving lesser surge current and energy to be discharged through the surge arrester. If there is still some concern of the dc surge

arrester to be inadequate in handling the surge energy, then two surge arresters in parallel with individual ground leads may be considered at the feeder poles [7]. However, an analysis of surge energy discharge through the surge arrester as discussed in Section V should be performed to determine the requirements for a second parallel surge arrester at the feeder poles.

The dc surge arresters applied at the dc feeder poles should be adequate to handle the discharge current of the lightning surge wave deposited by the lightning flash strokes. In addition, the dc surge arrester discharge voltage should be such that it provides adequate voltage margin of protection to the operating Light Rail Vehicle (LRV) and the traction power substations. Since these surge arresters at the OCS contact wire are first lines of defense to trap the lightning and switch surge voltage below the protection level of the connected equipment, it is recommended that an engineering analysis of surge arrester voltage ratings should be performed for proper selection of the surge arresters [7].

IV. LIGHTNING STROKE SURGE ENERGY

Surge energy (J) may be calculated by the expression [6]:

$$J = \int_0^t V \cdot I \cdot dt = \int_0^t \frac{dv}{dt} \cdot \frac{di}{dt} t^2 dt \quad \text{Joules} \quad (5)$$

Assume lightning stroke with the following parameters:

$$\frac{dv}{dt} = 200 \text{ kV}/\mu\text{s} \quad (2 \times 10^{11} \text{ V/sec})$$

Assume surge impedance for surge voltage to be near 40 ohms, parallel combination of OCS with supplementary feeder cable. Thus surge current wave by use of expression (4) will be as follows

$$\frac{di}{dt} = 5 \text{ kA}/\mu\text{s} \quad (5 \times 10^9 \text{ A/sec})$$

The maximum flashover kV peak for OCS is near 35 kV (dry weather condition), thus within 35/200 μs (0.18 μs), OCS poles will flashover to ground with or without the application of dc surge arresters.

Thus the lightning stroke energy that may pose threat of OCS damage or the dc surge arresters will be for flashover time of 0.18 μs with calculated stroke energy value indicated below.

$$t = 0.18 \mu\text{s} \quad (18 \times 10^{-8} \text{ sec})$$

$$J = 2 \times 10^{11} \times 5 \times 10^9 \times [t^3 / 3]_0^{18 \times 10^{-8}} \quad \text{joules}$$

$$J = 10^{21} \times 10^{-24} \times 18^3 \times 1/3 \text{ joules} = 5.83/3 \text{ kJ} \quad (6)$$

The OCS system appears to get self-relief from the heavy lightning stroke energy (responsible for damage to dc surge arresters and other OCS equipment) due to flashover near 35 kV peak surge magnitude without the help of surge arresters. However, 35 kV peak voltage is quite damaging to the system components, such as dc switchgear, and also LRV components. Thus dc surge arresters of proper rating should be applied. These surge arresters will discharge current and will handle energy as indicated in expressions (7) and (8) below.

V. ARRESTER DISCHARGE ENERGY

Arrester discharge current is a function of many interrelated parameters, including:

- Surge impedance of the OCS
- Stroke current characteristics, wave shape, peak current magnitude, and its rate-of-rise
- Distance of the surge arrester from the point of stroke
- Ground resistance at the location of stroke
- Number and locations of flashovers
- Flashover characteristics of the OCS insulators
- Arrester discharge voltage

The following expression [2] has been used for power distribution overhead lines and may be used for the OCS system:

$$I_A = (E_S - E_A) / Z \quad (7)$$

Where:

E_A = Arrester switching impulse discharge voltage (kV) for current I_A (kA)

E_S = Prospective switching surge voltage (kV)

Z = Surge impedance of the OCS wire (Ω)

I_A = Switching impulse current (kA)

Energy discharged by the arrester, J, in kilojoules (kJ), may be conservatively estimated by the following expression [2]:

$$J = 2 D_L E_A I_A / v \quad (8)$$

Where:

E_A = Arrester discharge voltage (kV)

I_A = Switching impulse current (kA)

D_L = Line length (miles) or (km)

v = the speed of light (190 miles/ms) or (300 km/ms)

The expression assumes that the entire line is charged to a prospective switching surge voltage and is discharged through the arrester during twice the travel time of the line.

If the surge wave shape is known, then another easier expression for the energy discharged through an arrester may be calculated by using the following expression [7].

$$W = KV_C I \tau \quad (9)$$

K = Constant, 0.5 for triangular wave, 1.0 for rectangular wave and 1.4 for exponential decaying wave

W = Energy in joules

V_C = Clamping voltage in volts

I = Impulse current in amperes

τ = Impulse duration in seconds

VI. LIGHTNING STROKE TO LRT SYSTEM

For analysis purposes, assume maximum distance between the substations to be near 1 1/2 miles. Assume that there are surge arresters installed only at the feeder poles adjacent to each traction power substation, and there are no other poles between the substations that are equipped with surge arresters as shown in Fig. 1. A lightning strike hitting the OCS wire in the middle of two substations will more likely propagate equally with 1/2 the impinging surge current magnitude to each substation [8]. Thus, the surge will travel maximum distance of 3/4 mile before reaching a pole with dc surge arrester.

For 750V dc LRT system, consider a dc surge arrester rated at 2 kV duty cycle with MCOV rating near 1800 V dc with discharge voltage rated at 7.0 kV. This discharge voltage is the surge arrester test voltage, which is based upon 20 kA peak current of a standard 8x20 μ s wave.

Time in milliseconds to travel 3/4 mile will be $3/4 \times 1/190$ (4 μ s). The energy discharged through the surge arrester in kJ using expressions (7) and (8) may be calculated as shown below.

Assume surge wave is magnified to twice its magnitude (2 times 35 kV dry flashover value of OCS) due to open circuit condition of a sectionalizing dc disconnect switch. Using OCS surge impedance of 40 ohms (surge impedance of OCS wire in parallel with underground supplementary cable), and assuming surge arrester discharge voltage (7 kV) to be the test voltage at 20 kA peak, the discharge current I_A and surge energy discharge will be as follows:

$$I_A = (2 \times 35 - 7.0)/40 = 1.575 \text{ kA}$$

$$J = 2 \times 3/4 \times (1/190) \times 7.0 \times 1.575 \text{ kJ} = 0.088 \text{ kJ} \quad (10)$$

It should be noted that the time to travel 3/4 mile distance by the lightning stroke is very small and it is possible that the lightning stroke time may be longer than two times the travel time for 3/4 mile distance. Under such circumstances, the maximum estimated time for the lightning stroke should be used for estimating the energy discharge through the lightning arrester. The time $3/4 \times 2/190$ ms (8 μ s) used in calculating energy J in kilojoules should be increased to a reasonable value, say 300 μ s, the maximum estimated time the lightning flash containing more than an average of three strokes may exist. This will lead to calculated energy of 3.30 kJ, which will still be below 4.4 kJ (2.2 kJ/kV) value for a 2000V dc surge arrester. This estimation of surge energy is very conservative as the assumed value of surge time and arrester discharge voltage seems to be on the high side. However, dc surge arrester selection based upon such high energy discharge requirements will assure that the arrester will not be damaged by extreme lightning flash hitting very close to its location.

In the above calculation it has been assumed that lightning surge impinging the OCS wire will flash over to grounded metallic OCS poles once the surge wave voltage reaches 35 kV peak. Time to reach 35 kV peak will depend upon the rate of rise of lightning surge wave. If the rate of rise for example is near 200 kV/ μ s, then the time to reach 35 kV peak will be 35/200 μ s, which is far less than the travel time of 4 μ s for 3/4 mile distance. Thus, OCS wire will not charge more than 35 kV peak voltage unless the surge comes across an open circuit caused by open position of a disconnect switch. However, as the surge propagation time to reach open circuit location is quite higher than the time to develop 35 kV peak voltage at lightning flash striking location, the OCS pole flash will occur before double peak voltage (2x35 kV) is impressed upon the OCS contact wire. Thus, flashover phenomena will reduce the surge energy that will be discharged through the dc surge arrester.

To provide assurance that OCS wire flashing over occurs in case of a direct lightning strike impinging the system, it appears that horn type air gap arresters should be installed in the mid-point of the two traction power substations. Such air

gap horn type surge arresters do not pose any threat of dc leakage current or uncertainty of their damage due to ambient temperature. They need to be bonded to the OCS poles low resistance-grounding electrode by appropriately sized (not less than #6 AWG) 2 kV insulated cable to avoid jeopardizing the OCS double insulators criteria.

VII. SUPPLEMENTARY CABLE -SURGE VOLTAGE

In certain sections of the OCS, it is assumed that there will be underground supplementary feeder cable. Also, it is assumed that the average distance between the OCS contact wire and the underground feeder cable tap connection is in the order of approximately 400 feet. For calculation purposes, assume 4000 feet of positive dc supplementary cable which will require a total of eleven (11) OCS contact wire- to- feeder- cables tap connections, and total of nine (9) underground cable splices. The design may require a cable splice connection in the manhole from underground parallel feeder cable to OCS connections. Lightning surge withstand capability of such underground cable splices and the tap point connection of cable at the overhead OCS contact wire are of concern.

Analysis of the cable splices and cable connection to the OCS contact wire would require a derivation of the peak value of the lightning voltage wave. Then this value will be compared to the tolerable values of surge impulse voltages of the cable splices and cable- to- OCS connections.

The basic switching surge level (BSL) of the 2 kV cable is near 75 kV peak. Underground cable splice BSL levels to match with the cable BSL level are also available.

Assume the following:

$Z_{OCS} = 400$ ohms (OCS contact wire surge impedance)

$Z_C = 40$ ohms (cable surge impedance)

$V_i =$ Voltage magnitude of the incident lightning wave at the impedance junction point (connection of cable to OCS contact wire or at the underground cable splice)

$I_i =$ Current magnitude of the incident lightning wave at the impedance junction point

$V_r =$ Voltage magnitude of the reflected lightning wave at the impedance junction point

$I_r =$ Current magnitude of the reflected lightning wave at the impedance junction point

$V =$ Total voltage magnitude (refracted voltage) at the impedance junction point

$I =$ Total current magnitude (refracted current) at the impedance junction point

The following expressions are well documented [6].

$$V = V_i + V_r \quad (11)$$

$$I = I_i + I_r \quad (12)$$

At the interface of two surge impedances Z_1 and Z_2 , the expressions for the above indicated surge voltage and current are related by the following expressions:

$$V = [2x Z_2 / (Z_1 + Z_2)] V_i \quad (13)$$

$$I = [2x Z_1 / (Z_1 + Z_2)] I_i \quad (14)$$

For the sake of completeness, expressions for the surge current as well as the surge voltage have been described. However, analysis of the surge wave voltage is more critical for the cable insulation protection when compared to surge current. It is well understood that the cable can tolerate excessive magnitude of surge current for short duration without appreciable heat rise to create damage to cable insulation. Hence, only the surge voltage analysis is presented in this paper.

A. Case #1: Lightning hits contact wire ahead of the supplementary cable connections.

The initial and final surge voltages at the junction points of cable to OCS or splice point may be calculated by using expression (13).

$$Z_1 = 400 \Omega, \text{ and } Z_2 = 40 \Omega$$

If all cable to OCS taps is spaced equally and the installation is uniform, then, for practical purposes, the combined surge impedance (Z) of underground supplementary feeder cable and OCS contact wire may be represented by expression (15).

$$Z = Z_1 \times Z_2 / (Z_1 + Z_2) \approx Z_2 \quad (\text{since } Z_1 \gg Z_2) \quad (15)$$

If voltages (V_1), (V_2), (V_3) and (V_{11}) are successively represented as voltages at the first, second, third and last (eleventh) junction point when the surge voltage travels along the OCS section with underground supplementary positive cables, the expressions for these voltages will be as follows:

$$V_1 = [2x Z_2/(Z_1 + Z_2)] V_i \quad (16)$$

$$V_2 = [2x Z_2/(Z_1 + Z_2)][2x Z_2/(Z_2 + Z_2)] V_i \quad (17)$$

$$V_3 = [2x Z_2/(Z_1 + Z_2)][2x Z_2/(Z_2 + Z_2)]^2 V_i \quad (18)$$

$$V_{10} = [2x Z_2/(Z_1 + Z_2)][2x Z_2/(Z_2 + Z_2)]^9 V_i \quad (19)$$

Using ohm values indicated for the surge impedances, surge voltages represented by expressions (16) through (19) will be practically equal in magnitude, approximately 18% of the incident stroke surge voltage magnitude.

The final (eleventh) point will be end of the supplementary cable where the surge impedance will become again Z_1 and the surge voltage will be escalated as follows:

$$V_{11} = [2x40/(400+40)].[2x400/(400+40)]V_i \quad (20)$$

This final voltage appears to be approximately 33% of the initial surge voltage.

If installation of the underground feeders and OCS connections is uniform, then the surge impedance will be practically the same, slightly less than 40 ohms. The above calculations indicate that voltage will never be more than the striking voltage unless there is a switch that may be in an open position to make this voltage two times the initial voltage. This twice the initial voltage can be derived by using the expression (13) as shown below.

$$V = [2x Z_2 / (Z_1 + Z_2)] V_i = [2/(Z_1/Z_2 + 1)] V_i \quad (21)$$

Since Z_2 at open switch will be infinite, thus Z_1/Z_2 will become zero in expression (21) making surge voltage V as two times the initial voltage V_i . These surge voltage calculations do not take into account the effect of surge attenuation due to cable inductance and capacitance effect.

If we assume that the striking voltage is limited to 35 kV by the flashover phenomenon, then it appears that the underground cable splices and the OCS-to-supplementary feeder cable tap connections may not require surge protection, except the first and the last connection points.

B. Case #2: Lightning stroke hits the OCS section in any location within the section of OCS to underground supplementary cable.

The surge voltage analysis for this case will be identical to the above analysis, and surge propagates to each side traversing the cable taps and underground splices. The current surge that propagates in each direction is practically half the magnitude of the stroke current. The associated surge voltage analysis calculations will be identical to the

calculations indicated under Case #1. The final maximum surge voltage will at the outermost cable-to-OCS connection tap points, and it will practically become double the traveling surge voltage as indicated by the following calculation.

$$V = [2x 400 / (400 + 40)] V_i = 1.82x V_i$$

This voltage V will be equal to lightning stroke surge voltage, which initially split into half the magnitude at the strike locations. All intermediate tap points will see a lesser amount in the order of 9% magnitude of the lightning stroke.

Thus, if the OCS flashover voltage is near 35 kV without the application of the dc surge arresters, then the maximum surge voltage will be near 35 kV peak or 70 kV if there is a switch that will be in an open position.

C. Surge Propagation Discussion:

More surge current may tend to propagate through the underground supplementary cable as compared to the OCS wire; however, the speed of surge propagation through OCS wire is two times the speed of surge through feeder cable. This may lead to balancing out the surge energy propagation through OCS and underground feeder.

It should also be mentioned that the underground cable switching surge peak impulse voltage withstand level far exceeds 35 kV peak surge wave that can be expected without considering the doubling effect. Thus it is not necessary that dc surge arresters be applied at every 400 feet at cable-to-OCS connection locations. However, doubling peak voltage effect cannot be avoided, especially if the dc disconnect switches are in open position. Thus at such locations, dc surge arresters are recommended.

It is the author's opinion that guesswork and overconcern of lightning protection without performing surge analysis indicated in this paper has led to a design of applying surge arresters at each OCS-to-supplementary cable tap. Such a design should be avoided based upon the surge voltage analysis presented in this paper. Addition of such excessive number of dc surge arresters to the OCS is an application concern, especially when such surge arresters do not have any indication means to tell visually that the arrester is in a degraded mode and may be injecting undesirable dc stray current to ground.

VIII. RECOMMENDATIONS

- 1) Considering the low profile of OCS, proximity of all components, inherently grounded poles, and major portion of the dc rail transit system close to high-rise

structures and trees, the probability of lightning striking the OCS is very low. With this configuration, application of the ground shield wire above the messenger and contact wire does not appear to provide any greater degree of protection, especially when the lightning strike tends to flashover the grounded structures.

- 2) It should be noted that MOV surge arresters are sensitive to ambient temperature. In the summer when ambient temperature is high, metallic tip of the MOV dc surge arrester may become hot leading to transfer of heat to the surge arrester material. This may cause premature surge arrester failures. Thus the installation should consider excessive temperature effect on performance and selection of MOV surge arresters.
- 3) MOV dc surge arresters should be installed at the following locations:
 - At feeder poles, close to pole-mounted or pad-mounted dc disconnect switches on load side of the switches.
 - At pole-mounted or pad-mounted OCS sectioning switches. Arrester may be installed on either side of the switch.
 - At dc switchgear on load side of the dc feeder breakers. These surge arresters should be applied with appropriate fuses to avoid the danger of hazard in case surge arrester fails due to internal thermal damage. It may be wise to install such arresters on outside walls of substation housing.
 - At vehicle pantograph, roof mounted surge arresters. Such units are an integral part of the vehicle system and their ratings should be reviewed to assure they are adequate for the lightning protection.
 - For LRT system within high isokeraunic areas, consider installing surge arresters at the negative bus box to protect the equipment under rare circumstances of lightning surge reaching the negative bus box via running rails and dc feeder cables.
 - Install dc surge arrester at the first and last OCS to underground positive supplementary feeder cable tap location.
 - For high isokeraunic areas, consider application of horn type air gap arresters at the middle point of the adjacent substations or other locations such as bridges, tunnels, etc. Such arresters do not pose the threat of dc leakage current unlike the MOV type dc surge arresters.

- 4) An engineering analysis should be performed to determine appropriate voltage rating of the dc surge arresters [7]. The analysis should take into consideration the LRT location, ambient environment and operating voltage characteristics.
- 5) Lightning protection analysis should be performed to avoid guesswork and misapplication of dc surge arresters when designing lightning protection scheme for a rapid transit system.
- 6) MOV dc surge arresters are continuously conducting low level of current to ground. This current may increase if the internal material becomes defective. Future development of dc surge arresters should provide visual indication when the surge arrester becomes defective or fails so that it can be removed to avoid the uncertainty of draining continuous low-level dc stray current to ground.
- 7) Appropriate ac surge arresters at the utility feed point as well as close to rectifier primary windings as shown in Fig.1 should also be applied to protect LRT substation equipment from lightning [11].

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Figure 1 - DC Rapid Transit System - Traction Power Distribution One Line Diagram