LIGHTNING AND SWITCHING TRANSIENT OVERVOLTAGES IN POWER DISTRIBUTION SYSTEMS FEEDING DC ELECTRIFIED RAILWAYS

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Abstract-Control and reduction of the voltage transients in power distribution systems feeding electrified railways are a significant issue. Therefore, it is necessary to study how and why the voltage transients are injected to the system and how they can be reduced. In this paper, the switching and lightning overvoltage transients of DC electrified railways are studied and investigated and the selection of qualified DC surge arresters and their best point of connection to the electric system are recommended. Later on, through the simulation results done with PSCAD/EMTDC the efficiency of the selected and installed surge arresters with the proposed characteristics is verified.

Keywords- Electric power distribution systems, DC electrified railways, Lightning and switching transient overvoltages, Surge arrester

I. INTRODUCTION

Overvoltages are one the most significant problems in the power distribution system of electrified railways where the investigations on why they are generated and dispersed in the power system and how they can be controlled and reduced are conducing. Lightning overvoltages are one of the most probable overvoltages that are caused due to the direct strike of the lightning to the overhead contact system of the railway or its occurrence in the system neighborhood. Switching overvoltages due to the switching phenomena in the traction substations are also another major source of overvoltage generation in these systems. These overvoltages can be dangerous for the electrical equipment of the traction system if not controlled and reduced effectively.

On the other hand, in some cases the high density of the charged clouds in the sky above the overhead contact system of the railways has also been able to cause effective overvoltage transients that have even resulted in the flashover on the insulators. In some cases, the lightning overvoltages have even been able to penetrate to the grounded return current cables of the traction system which has caused some problems at the traction substations. It has been also seen that the high voltage transmission lines that are in parallel with the overhead contact system of the railways are some times the source of overvoltage generation in the power distribution system of electrified railways since due to any unbalance and failures in the high voltage system, some induced voltages are generated and dispersed in the power distribution system of electrified railways. Therefore, it would be of great importance to study the effects of the transient overvoltages in these systems and investigate different methods for controlling and minimizing them to prevent any electrical failures in the traction system.

Application of surge arresters in the power distribution system of electrified railways would be one of the best solutions for control and reduction of the transient overvoltages in these systems. But appropriate selection of the surge arresters for DC and AC electrified railways and the best point of their installation is of great importance. The selected equipment should be capable of absorbing all the energy of the transient overvoltages to prevent any failure in the other electrical equipment of the traction system especially in traction substations and also flashover prevention over the insulators.

In this paper, the switching and lightning overvoltage transients of DC electrified railways are studied and the selection of qualified DC surge arresters and their best point of connection to the electric system are investigated and recommended. Later on, through the simulation results done with PSCAD/EMTDC the efficiency of the selected and installed surge arresters with the proposed characteristics is verified.

II. DC ELECTRIFIED RAILWAYS

The power distribution system feeding DC electrified railways consist of the traction substations, overhead contact system and the feeder cables feeding the traction substations from the adjacent power network. The three phase power network is rectified through the rectifier units in the traction substations and feeds the moving trains along the route by means of the overhead contact system. The schematic diagram of the power distribution system feeding DC electrified railway system including the structure of the two adjacent traction substations are shown in Fig. 1. The electrical parameters of such a system are shown in Table 1.

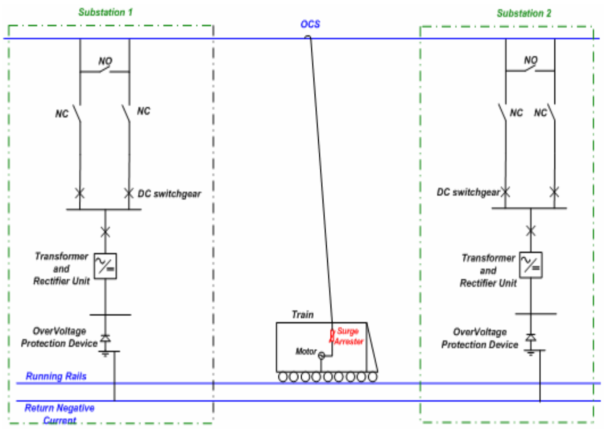

Fig. 1. Schematic diagram of the power distribution system feeding DC electrified railways.

Table 1. The electrical parameters of the power distribution system feeding DC electrified railways

Nominal system voltage	800 V DC
No-load system voltage	848 V DC
Maximum voltage at regenerative breaking	1000 V DC
Traction substation transformer taps	±2.5%
System voltage regulation	±5%
Transformer and rectifier units loading	Continuous 100% Two hours 150% One minute 300%
Dielectric resistance of the rectifier unit	5 times nominal DC voltage
Dielectric resistance of the switchgear unit	5.9 times nominal DC voltage
Electric insulation level of feeder cables	2 or 5 kV DC
Electric insulation level of electric equipment in the train sets	3 kV DC

III. TRANSIENT OVERVOLTAGES

Overvoltage transients applied to DC electrified railway systems can effect the electrical equipment of the traction system and depending on their characteristic, stored energy and their duration. The overvoltages in these systems are not limited to lightning and switching but can be generated due to several other parameters which are transmitted through the overhead contact system or the cables and distributed to the traction substations and the running trains along the road. Therefore, it is necessary to prevent any electrical equipment failures due to the distributed transient overvoltages by applying qualified surge arresters.

The standards make a definition between switching and lightning overvoltages based on the duration of front and tail times of the generated surges where surges with fronts till 20 µsec. are the results of lightning and the surges with front time above 20µsec. are due to switching overvoltages.

The most important reasons of transient overvoltages injected to the power distribution system of DC electrified railways are:

- DC circuit breaker operation can cause overvoltages of 2.5 times the system nominal voltage.
- Uneven pantograph contact can also result in arcs and overvoltages in the overhead contact system.
- Vacuum circuit breaker operation can also result in overvoltages in the power system of electrified railways.
- Direct lightning or heavy lightning in the neighborhood or even heavily charged clouds in the sky above the overhead contact system of the railway can result in overvoltages in this system.
- Loose connection of the electrical equipment can result in the arcs and overvoltages in the system.
- Current limiting fuses applied as protection devices in traction substation can also cause arcs and overvoltages at operation times.
- The voltage transients due to *dv/dt* across the diodes of the rectifier units in traction substation can also result in overvoltages in the power system.

IV. DC SURGE ARRESTER CHARACTERISTICS

The applied DC surge arresters for protection of the power distribution system of DC electrified railway systems should fulfill the following characteristics:

- Should not conduct at system nominal voltage and should have minimal leakage current
- Should conduct at the immediately overvoltages of the system while permitting only small increase in its own terminal voltage
- Be capable of handling and controlling high amount of energy stored in DC systems
- Be capable of application at different environmental conditions especially the humidity of the tunnels
- The residual voltage of the device at maximum expected overvoltage should be less than the damaging voltage of the device.
- Should have no failures at the overvoltages of the system

Taking into account the mentioned characteristics for the qualified DC surge arrester, only the surge arresters with the characteristics curve shown in Fig. 2B is appropriate for DC electrified railway systems since not only it has a close characteristic to ideal devices (Fig. 2A) but can protect the system even in lower overvoltage values resulting in higher accuracy (as shown in Fig. 2D) and prevent any failures on the operation at system overvoltages which might occur for the surge arrester with the characteristic shown in Fig. 2C.

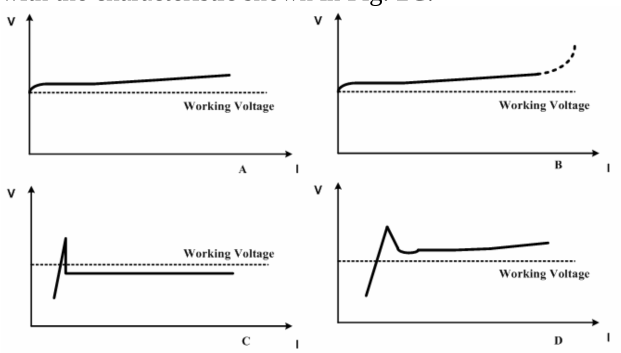

Fig. 2. Characteristics of surge arresters: a) Ideal device, b) Metal oxide, c) Spark gap, d) Gapped metal oxide.

Lightning or switching overvoltages in the OCS cause a high energy injection to the power distribution system of the electrified railways that are dependent to the traction system structure and surge impendence of the OCS. Utilizing appropriate surge arresters, the injected energy can be passed away. The surge impedance of the OCS can be written as:

$$Z = \sqrt{\frac{L}{C}} \tag{1}$$

where L is the line inductance and C is the line capacitance in Hanries and Farads per unit length, respectively. The surge waves transfer the OCS lines in almost light speed and in any junction, some extenct of the waves are broke and some is reflected. Therefore, the voltage magnitude due to overvoltages that reaches the transformers in the traction substations through the OCS and cables (V_{FC}) is calculated by:

$$V_{FC} = 2V_I\left(\frac{Z_c}{nZ_{ocs} + Z_c}\right) \tag{2}$$

where Z_C is the surge impedance of the cable, Z_{OCS} is the surge impedance of the OCS, n is the number of the parallel cable feeders and V_I is the magnitude of the surge voltage.

The installed DC surge arresters should be capable of absorbing the maximum energy of the switching and lightning transient overvoltages which are equal to:

$$U_{50\%CZ} = \frac{1.05U_{b.p}.K_d}{(1-3\sigma_z)K_h} \tag{3}$$

$$U_{50\%L} = \frac{1.1\times 1.25K_d}{(1-3\sigma_L)K_h}U_{b.c} \tag{4}$$

where $U_{50\%CZ}$ is half of the positive switching impulse discharge voltage, $U_{b.p}$ is the protection level for switching impulses, $\sigma_z = 0.05$ is the constant coefficient of the positive switching impulse variations, $U_{50\%L}$ is half of the positive lightning impulse discharge voltage, $U_{b.c}$ is the protection level for lightning impulses and $\sigma_L = 0.05$ is the constant coefficient of the positive lightning impulse variations and K_d and K_h are given as:

$$K_d = \delta^m \tag{5}$$

$$K_h = \left[1 + a(\frac{h}{\delta} - 11)\times 10^{-3}\right]^w \tag{6}$$

where K_d and K_h are the air density and humidity factors, respectively and $m=1$, $w=1$, $a=8$ are the constant coefficients for lightning impulses, h is the absolute humidity [gr/m^3] and δ is the relative air density.

Therefore, the maximum energy of such a surge arrester is calculated by:

$$W = \int_0^t V.I.dt \tag{7}$$

where V is the front of the wave protective level of the surge arrester, I is the maximum discharge current of the surge arrester and t is the time interval that the surge reaches the voltage V.

Another experimental method for determination of the rating of the surge arrester is calculated by:

$$W = K.V_c.I.t \tag{8}$$

where $K=1.4=Const.$, V_C is the clamping voltage in Volts, I is the peak applied current [A] and t is the impulse duration [sec].

V. SURGE ARRESTER INSTALLATION POINTS

As shown in Fig. 1, the overvoltage transients can penetrate the electrical equipment of the traction substation easily. Therefore, the maximum overvoltage amplitude that can reach the traction substation through the overhead contact system without any installed surge arresters in equal to dry flashover voltage of the overhead contact system. In addition, the overvoltage of the AC system which reached the traction substation through the AC power network will be doubled due to the impedance variation at the transformer and rectifier unit. On the other hand, the lightning strike can cause overvoltages to be dispersed in both of the overhead contact system and the running rails as the positive and negative phases of the feeding system respectively, which would transmit to the running train sets and the traction substations.

Therefore, according to the penetration points of the overvoltages, the best points of installation of DC surge arresters are (as shown in Fig. 3):

- Primary terminal of the transformer and rectifier units in the traction substation
- AC input of the diode rectifier bridges accompanying with current limiting fuses
- DC output of the rectifier units accompanying a reverse diode graded capacitor
- Protection of DC switchgear
- The connection point of the rectifier outputs to the overhead contact system of the railway
- The input point of the overhead contact system to the train sets
- Protection of running rails only for the areas with high Isokeraunic value

Utilizing DC surge arresters with the characteristics pointed out in part IV and installing them at the selected points of part V would reduce the transient overvoltages greatly.

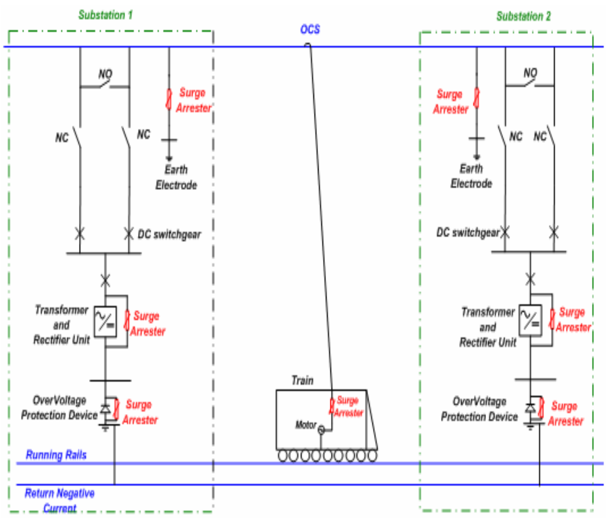

Fig. 3. The best points of installation of surge arresters in the power distribution system of DC electrified railways.

VI. STUDY CASE AND SIMULATION RESULTS

It is essential to study the efficiency of the proposed structure and characteristics of the DC surge arresters at the proposed installation situations and prove their great effects on reducing the transient overvoltages. For this purpose, PSCAD/EMTDC simulations are done for the power distribution system feeding DC electrified railway as shown in Figures 1 and 2 for the distribution system without and with installed surge arresters, respectively. The system parameters were as shown in Table 1 and the lightning impulse injection to the both AC power network and DC overhead contact system of the railway system were studied.

Through the simulation results, it is proved that when a lightning has attached one of the phases of AC power network, the transient overvoltages on that phase and the induced voltages on the other phases are transferred through the rectifier units in the traction substation to DC overhead contact system as shown in Figures 4-6.

Studying the results of the simulations done for the same power system with installed surge arresters proves their efficiency in controlling and reducing the transient overvoltages in these systems. For instance, the waveforms of the AC power network, the voltage over the diodes in the rectifier unit of the traction substation and also the DC voltage waveform of the overhead contact system with installed surge arresters are shown in Fig 7-9.

It is also proved that when the lightning attachment has occurred at DC overhead contact system of the traction system, due to the application of diodes in the rectifier structure of the traction substations, the overvoltage transients can not be transferred back to AC power network but are transmitted along the contact system and fed to the traction motors in the train sets. The results of the simulations for this case are shown in Figures 10-12 (without installed surge arresters) and Figures 13-15 (with installed surge arresters)

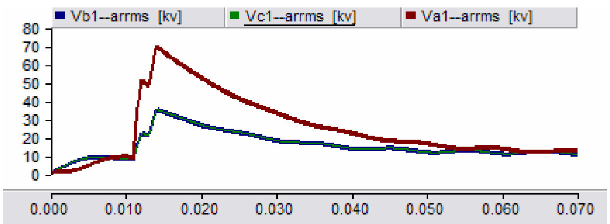

Fig. 4. Three phase voltage waveforms of the AC power network in the case of no installed surge arresters when the lightning has been attached to the AC side of the traction substation.

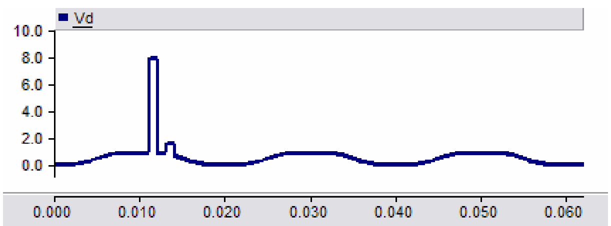

Fig. 5. Voltage waveforms of the rectifier unit diodes in the traction substation in the case of no installed surge arresters when the lightning has been attached to the AC side of the substation.

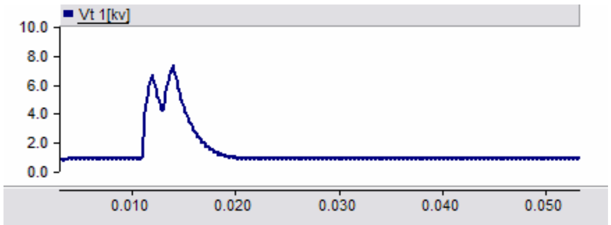

Fig. 6. DC voltage waveform of the overhead contact system of the railway in the case of no installed surge arresters when the lightning has been attached to the AC side of the traction substation.

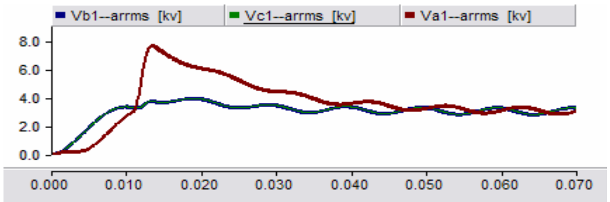

Fig. 7. Three phase voltage waveforms of the AC power network in the case of installed surge arresters when the lightning has been attached to the AC side of the traction substation.

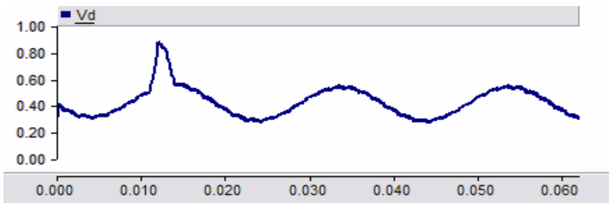

Fig. 8. Voltage waveforms of the rectifier unit diodes in the traction substation in the case of installed surge arresters when the lightning has been attached to the AC side of the substation.

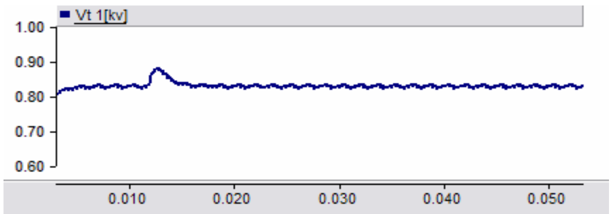

Fig. 9. DC voltage waveform of the overhead contact system of the railway in the case of installed surge arresters when the lightning has been attached to the AC side of the traction substation.

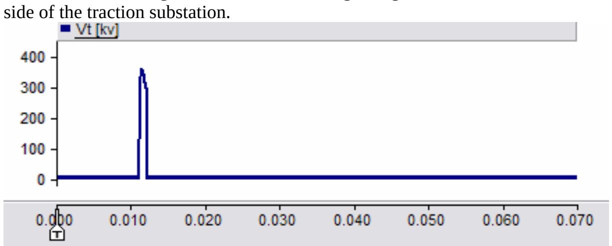

Fig. 10. DC Voltage waveform of the overhead contact system of the railway in the case of no installed surge arresters when the lightning has been attached to the DC side of the traction substation.

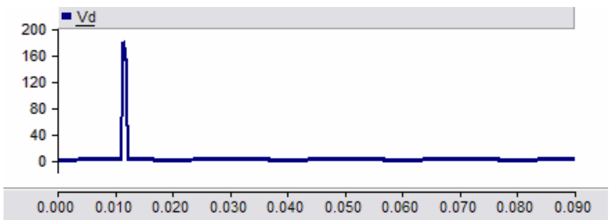

Fig. 11. Voltage waveforms of the rectifier unit diodes in the traction substation in the case of no installed surge arresters when the lightning has been attached to the DC side of the substation.

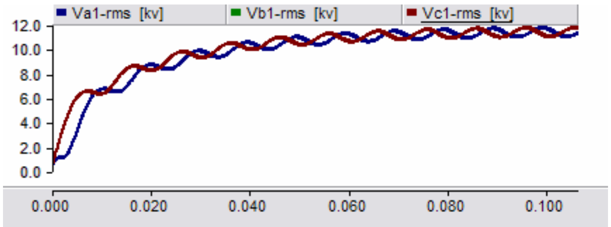

Fig. 12. Three phase voltage waveforms of the AC power network in the case of no installed surge arresters when the lightning has been attached to the DC side of the traction substation.

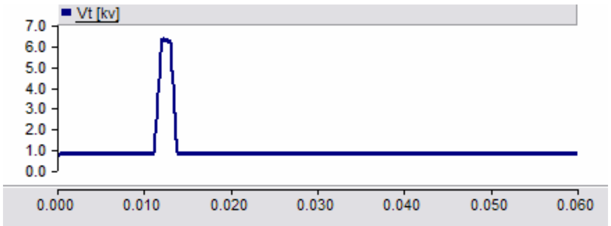

Fig. 13. DC Voltage waveform of the overhead contact system of the railway in the case of installed surge arresters when the lightning has been attached to the DC side of the traction substation.

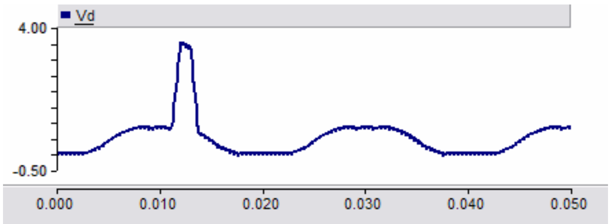

Fig. 14. Voltage waveforms of the rectifier unit diodes in the traction substation in the case of installed surge arresters when the lightning has been attached to the DC side of the substation.

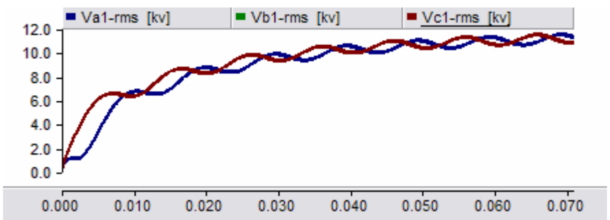

Fig. 15. Three phase voltage waveforms of the AC power network in the case of installed surge arresters when the lightning has been attached to the DC side of the traction substation.

VII. CONCLUSION

Overvoltages as one of the most important problems of the power distribution systems of electrified railways were studied in this paper. Since the higher values of the generated transient overvoltages can cause great problems for the electrical equipment of the traction system, it is necessary to control and reduce of the voltage transients. Therefore, the lightning and switching overvoltage transients as the most common overvoltage transients in DC electrified railways were studied and the application of MOA DC surge arresters were investigated. In addition, the characteristics of qualified DC surge arresters and their best point of connection to the electric system were recommended. Later on, through the simulation results done with PSCAD/EMTDC the efficiency of the selected and installed surge arresters with the proposed characteristics were verified.

VIII. REFERENCES

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