Analysis of the Pantograph Arcing on the Railway Vehicle

Mustafa Karagöz1, Mirzahan Hızal2
1Defense System Technologies Sector, ASELSAN, Ankara, Turkey
2Hızal Electricdischarge Industry & Trade Ltd., Ankara, Turkey

Abstract— In this paper, pantograph arcing and effects of pantograph arcing on the railway vehicles are investigated. Sliding contact between the pantograph contact strips and the catenary contact wire is described with the emphasis on the pantograph arcing. Electric arc is examined in details. Arc characteristics, formation methods, extinction and reignition of the arc are studied. An experimental test setup is designed and implemented to be used in this work. Results of the experiments are presented and discussed.

Keywords— Pantograph arcing; arc discharge; railway traction system;

I. INTRODUCTION

The purpose of the pantograph is to transfer power from the contact line to the electric traction unit. The transfer of the power has to be safe and reliable both in a stationary condition for auxiliary and convenience power and for motive power to the operation of the traction vehicle.

The sliding contact between pantograph and overhead contact wire is a critical interface between train and infrastructure in an electrified railway. As well as requiring correct tensioning and geometry, it is necessary to eliminate imperfections and obstruction from the contact wire. Such discontinuities can be developed due to various reasons and may lead to pantograph arcing [1].

The interaction between the overhead contact wire and the contacts of a pantograph determines the quality and reliability of the energy transmission to traction units. This interaction depends on the design of the overhead contact line and the pantograph. High speed trials have shown that the pantograph-contact line interaction is of extreme importance because energy transmission is a factor that could limit the maximum speed achieved. In May 1991, an SNCF train of an enhanced TGV-Atlantique type achieved a speed of 515 km/h and set a world speed record for railway vehicles. During preparatory runs the importance of the contact line design became apparent. The trial had to be aborted a speed of approximately 480 km/h due to current interruptions caused by contact wire uplift values of more than 300 mm [2]. Pantograph arcing causes interruption of the power supply because of this wire uplift.

The estimation of contact wire wear must take into account in the variation of electrical contact resistance together with radius of contact spots and contact force. The increasing contact force reduces the contact resistance and arcing but increases the plate and wire wear rate. The experimental results of [3] and [4] also support this idea.

Similar with overhead transmission line conductors, ice layers with thicknesses up to ten millimeters can be formed on the conductors of overhead traction lines. Ice accretion may affect the operation only where the headway between trains with pantographs in contact is more than 15 min.

The ice accretion on contact wires forms an insulating layer which cannot be penetrated by the pantograph. However, the current will not be completely interrupted but flows across arcs between the contact wire and the collector strips. Therefore, the current flow causes erosion and current burn marks at the edges of the contact elements on the contact wire and the collector strips.

Arcing from pantograph is commonly observed throughout the year. However, factors like the increase in the train speed, current and especially cold weather conditions contribute to increase the visibility of the pantograph arcing.

The pantograph arc current generates significant low and high frequency current components because of the arc nonlinearity [5]. Pantograph arcing causes radiated interference with the wireless and radio communication services. It also causes conducted interference with railway signaling systems, power supplies and nearby grounded structures through its return path [6]. Saturation of the transformer core is another consequence of pantograph arcing.

II. ELECTRIC ARC

A metal contains mobile electrons in a partially filled band of energy levels—i.e., the conduction band. The energy that is required to release a mobile electron from the metal varies from about 1.5 to approximately 6 electron volts, depending on the metal. In thermionic emission, some of the electrons acquire enough energy from thermal collisions to escape from the metal. The number of electrons emitted from the metal depends critically on temperature [7]. The work function of the metal which is the required energy to remove an electron from the metal denoted W, and it is expressed in joules (eV).

Richardson’s law is almost valid for all metals. It is usually expressed in terms of the emission current density (J) as
\[ J = A T^2 e^{-W/kT} \]  

in amperes per square meter. The Boltzmann constant “\( k \)” has the value \( 8.62 \times 10^{-5} \) electron volts per Kelvin, and temperature “\( T \)” is in Kelvin. “\( A \)” is the Richardson constant expressed in A.m\(^{-2}\).K\(^{-2}\). In theory, the Richardson constant would be equal to \( 1.2 \) MA.m\(^{-2}\).K\(^{-2}\), but in practice, because the work function is also a function of temperature, “\( A \)” varies over a wide range of magnitude.

### TABLE I. THERMOIONIC PROPERTIES OF SELECTED MATERIALS (ADOPTED FROM [8])

<table>
<thead>
<tr>
<th>Material</th>
<th>Electron work function (W/eV)</th>
<th>Richardson constant (A/kA.m(^{-2}).K(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>5.0</td>
<td>150</td>
</tr>
<tr>
<td>Copper</td>
<td>4.65</td>
<td>1200</td>
</tr>
</tbody>
</table>

When the electron work function and Richardson constants of pantograph contact strip material carbon and overhead contact line material copper compared, it can be said that emission current density of copper is higher than carbon. Therefore, it can be said that it is easier to liberate electrons from the copper.

### III. EXPERIMENTS

#### A. Experiment Setup Configuration

Pantograph arcing experiment setup configuration is shown in Fig. 1. A brass contact line which is fixed around a wheel is used to simulate the overhead contact line and a carbon strip is used to simulate the pantograph contact strip. The setup is designed and implemented to simulate the interaction between a pantograph and overhead contact line as similar as the real case. To ensure uniform and low wear of the pantograph collector strips and the contact wire, the contact wire has to be installed with a lateral offset to the projected track centre line. Therefore, the speed of pantograph has two components, one of them is on longitudinal axis and the other one is on latitudinal axis. For that reason, there are two electric motors in the test setup. One of them is connected to center of the wheel and the other one to the carbon strip with belt-pulley systems. The speed of the motor which drives carbon strip laterally is controlled by a motor controller unit.

The high voltage is supplied from a 100V/15000V step-up transformer. The transformer voltage is controlled by a variac which is integrated into the control unit of the high voltage supply. The output voltage of the step up transformer is measured with a resistive voltage divider to arrange the input voltage. Also two capacitive voltage dividers are used in the test setup. Divider-1 is used to measure the voltage of the contact line and the other one, divider-2, is used to measure the voltage of the carbon strip. In this way, the voltage difference of these two capacitive dividers gives the arc voltage. Furthermore a 10Ω current shunt resistor is used to measure the current circulated in the circuit. A 15000V/100V step-down transformer which simulates the train transformer, is fed from the carbon strip. An adjustable load is connected to the low voltage side of this step-down transformer. The power factor of load can also be arranged in this way.

A four channel 300 MHZ, 2.5 GS/s digital oscilloscope is used for the voltage and current measurements. The capacitive dividers are designed with a 149 ratio. However, they are calibrated with the help of a high voltage probe and oscilloscope which are both have a valid calibration certificate. The measurement ratios of the instruments are given in Table II. During the tests, the parameters given in Table III are measured with the oscilloscope.

#### TABLE II. INSTRUMENTS’ MEASUREMENT RATIOS

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divider-1</td>
<td>147</td>
</tr>
<tr>
<td>Divider-2</td>
<td>149</td>
</tr>
<tr>
<td>Current Shunt Resistor</td>
<td>0.1 A/V</td>
</tr>
</tbody>
</table>

#### TABLE III. MEASURED PARAMETERS

<table>
<thead>
<tr>
<th>Measured Parameters</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step-up transformer HV side voltage</td>
<td>Divider-1</td>
</tr>
<tr>
<td>Carbon strip voltage Divider-2</td>
<td>Divider-2</td>
</tr>
<tr>
<td>Current</td>
<td>Current shunt resistor</td>
</tr>
<tr>
<td>Step-down transformer LV side voltage</td>
<td>Low voltage probe</td>
</tr>
</tbody>
</table>

![Fig. 1 Schematic of pantograph arcing experiment setup](image1)

![Fig. 2 Pantograph arcing test setup photograph](image2)

#### B. Arcing Experiments

Five of the conducted pantograph arcing tests are selected to investigate the effects of parameters on pantograph arcing.
TABLE IV: TEST PARAMETERS

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>Test-1</th>
<th>Test-2</th>
<th>Test-3</th>
<th>Test-4</th>
<th>Test-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage</td>
<td>10 kV</td>
<td>10 kV</td>
<td>10 kV</td>
<td>10 kV</td>
<td>10 kV</td>
</tr>
<tr>
<td>Distance between</td>
<td></td>
<td>1 mm</td>
<td>1 mm</td>
<td>1 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>contacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistive load</td>
<td>20 Ω</td>
<td>20 Ω</td>
<td>10 Ω</td>
<td>10 Ω</td>
<td>20 Ω</td>
</tr>
<tr>
<td>Inductive load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.34 Ω</td>
</tr>
</tbody>
</table>

Harmonic frequency histograms of measured currents for test-1 to test-5 are given in Fig. 3. Test results shown that current has both even and odd harmonics because of arcing.

The pantograph arcing current waveform of test-2 is given in Fig. 4. The current has peaks every half cycle due to arcing.

Arc voltage waveform of test-2 is shown in Fig. 5. When the experimental results of arc voltages of the positive and negative half cycles are compared, it can be said that they are not symmetrical. The arc voltage at positive half cycle is greater than the negative half cycle in this experiment.

IV. DISCUSSION

To understand the effects of transformer on the voltage at the test setup, harmonic contents of the HV input and LV output signals of transformer is compared using FFT function of an oscilloscope. Comparing the harmonics on both sides of the transformer, it can be said that transformer has very little contribution to the harmonic content of the voltage.

A track circuit is a simple electrical device used to detect the absence of a train on rail tracks. Track circuits are used to inform signalers and control relevant signals. The track circuit based signaling systems are operating using the dc or even harmonic of the traction power frequency. Test results shows that pantograph arcing distorts the sinusoidal current waveform. During the current zero crossings of the ac supply voltage arc is extinguished and after the voltage reaches enough magnitude it reignites again. Between these two events current remains at zero. This causes both even and odd harmonics on the current as it is shown in Fig. 3. Therefore, pantograph arcing can cause conducted interference with the track signaling systems. False signaling in the railways may cause accidents and delays in the rail operations. Same problems are also covered in [9].

The pantograph arcing current waveform of test-2 is given in Fig. 4. The current has peaks every half cycle due to arcing. Pantograph arcing may also cause the wrong opening of the protective circuit breakers due to these current peaks. This is another problem of pantograph arcing. Similar problems are also mentioned in [10] and [11].

Arc voltage waveform of test-2 is shown in Fig. 5. When the experimental results of arc voltages of the positive and negative half cycles are compared, it can be said that they are not symmetrical. The arc voltage at positive half cycle is greater than the negative half cycle in this work. The current is 10 mA in the test setup. Therefore, the line and carbon contact are at the same temperature. With the help of Richardson’s law, and thermionic properties of carbon and brass (copper alloy), it can be said that emission current density of brass is higher than carbon. Therefore, it is easier to liberate electrons from the brass (copper). Results of pantograph arcing experiments conducted by “OHL Ice Team” in Sweden also shows asymmetry between the arc voltages. However, they found that arc voltage is greater at negative half cycle opposite to the results of this work. At negative half cycle, carbon strip is anode and copper contact line is cathode. Since copper...
contact is always cool, it causes a lower rate of electron emission compared to the heated carbon when it is the cathode. Therefore, it can be concluded that the arc voltage is higher when the copper contact line is the cathode. In [8], experiments conducted by “OHL Ice Team” has a supply current of order of 10 A with the help of a more powerful voltage supply. On the other end, experiments conducted with supply currents order of 10 mA in this work. Therefore, the pantograph contact (carbon) was at a much higher temperature than the copper line in their work. This may cause a higher rate of thermionic emission from the carbon when it is the cathode resulting in a higher conductivity in the arc and a lower arc voltage as observed.

Test results showed that distortion in the supply voltage and current has a linear relation with contact separation between the pantograph and over head line. When no contact distance is set between the contacts, there is relatively small distortions in the voltage and current. However, with the increase in the contact distance, distortion in the voltage and current increased. In the tests 1, 2 and 5 contact distances are changed while the other variables are kept constant. The peak current increased. In the tests 1, 2 and 5 contact distances are increased with the contact separation. Therefore, visible arcs are observed. The pantograph equation breakdown voltages for 1 mm and 2 mm contact distance are found 7400 V and 13240 V, respectively. As Paschen law states, breakdown voltages increases with electrode separation. The conditions in the case of re-ignition of a self-sustained discharge by an alternating potential are vastly unlike those existing in the case of the original breakdown of the gas. In the arc plasma, the number of free ions is larger than those in the fresh gas. Therefore in the experiment reignition voltages are measured to be smaller than breakdown voltages of the gas for given contact distances. In conclusion, to reignite the arc, the required voltage increases with contact separation. These are also consistent with the train operation in summer and winter. In summer, pantograph arc is relatively slight since there is no ice between the contacts. On the other hand, at temperature below freezing point hoar frost can form on the conductors when enough moisture is in the air and wind is blowing against the lines. Also super-cooled rain and wet snow can lead to serve ice formation on the conductors. This ice layer increases the distance between the contacts. Therefore, visible arcs are realized in winters. Harmonic content of the pantograph voltage also increases with the contact separation distance. This is also related with the increase in the arc voltage.

In tests, increase in the arc current reduced the harmonic contents of both current and voltage. In the tests 2 and 4 load currents are changed with changing resistive load while the other variables are kept constant. The arc current is doubled in test 4. The peak values of the arc voltages are measured 5700V and 4050V, respectively. An AC arc may be extinguished or reignite after zero current crossings. The arc reignition arises from the birth of a new cathodic spot after zero current crossings. In principle, the generation of a new spot is not different from a first ignition of the arc, except that the extinguished arc may create circumstances which favor new births. For example, an electrode can be considerably hotter after the arc has operated for some time than it was before the first ignition. Mechanism of the cathodic spots is purely or essentially thermo-electronic. Arc reignition is easy as long as the temperature is still above a certain threshold when the conditions favorable to the reignition of an arc are restored. As the hot spot cools down, it is observed that the reignition becomes less and less possible. Reignition at the new cathode is helped considerably by the heat liberated at the old anode since they are one and the same surface. The active portion of the electrodes will have become heated, the extent of this heating is dependent on the current of the discharge. The degree of ionization at zero current is a direct function of the arc current. In the absence of a reappearing voltage, the ionization when the current is low will quickly disappear by recombination in the gas and neutralization at the electrode surfaces. For higher values of current, the volume deionization will be slower, because in the presence of thermal ionization, deionization will proceed at a much slower rate, determined by a time constant characteristic of the gas. Obviously, in the case of small current arcs, the reapplied voltage must be very much higher or must be applied at a much higher rate than for heavy currents if deionization is to be arrested. Therefore, an increase in the arc current causes a decrease in the arc voltage.

Results of the experiments also show that adding inductance to the circuit decreases the zero current regions time so the harmonic content of the current. The magnetic energy stored in the inductances of the load, forces the current to flow. Therefore, high voltage will appear across the arc during the extinction. In modern trains power factor of the traction unit can be arranged easily. Therefore during winter, when the visible arcs are observed, trains may be driven with a lagging power factor to reduce the arcing.

V. CONCLUSION

The objective of the traction power supply is to ensure uninterrupted, reliable and safe operation of the electric traction vehicle. The sliding contact between pantograph and overhead line is a critical interface between the train and high voltage power supply in an electrified railway.

Arcing from pantograph is commonly observed throughout the year. However, factors like increasing train speed, current and especially ice formation on the lines contribute to the pantograph arcing.

In this paper, pantograph arcing and some of the effects on the railway vehicle’s power supply were investigated. A test setup was designed and implemented to investigate the pantograph arcing phenomena. The effects of the parameters like contact distance, load current and power factor on the pantograph arcing were studied.

REFERENCES


