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Measurement of current flowing through a rail with the use of Ohm's method; determination of the impedance of a rail

***Abstract**. The article describes a method of measuring current flowing through a rail. This method is based on voltage drop measurement. For this method to be used correctly, it is necessary to know the resistance or impedance of the rail. A laboratory measurement was carried out, in order to determine the resistance and impedance of the rail, and subsequently a rail substitution diagram was created based on laboratory measurement results. A practical measurement on a railway track was performed to verify this substitution diagram as well as the whole designed measurement methodology.*

***Streszczenie.** W artykule opisano metodę pomiaru prądu płynącego przez szynę pojazdów trakcyjnych. Metoda wykorzystuje pomiar spadku napięcia a więc musza być znane rezystancja i impedancja szyny. (**Pomiar prądu płynące przez szynę pojazdów trakcyjnych – określanie impedancji szyny**)*

Keywords: Rail, Impedance, Measurement, Ohm's method.
Słowa kluczowe: pomiar prądu, impedancja szyny

Introduction

In electric railway traction (i.e. railways, trams), rails are usually used as conductors, conducing current that returns from railway vehicles back to a traction substation. In the course of this process, part of the current actually does not flow back through the rail but instead leaks into the ground and flows to the substation through the ground. This phenomenon, called stray currents, is very dangerous because it causes electrochemical corrosion that can damage under ground metal equipment. Recently our team has been working on the measurement of ground current fields and of current flowing from rails into the ground.

Ohm's method is used to measure currents in rails. It is based on voltage drop measurement on a specific rail, followed by current calculation. For this method to be used correctly, it is necessary to know the resistance of the rail in the case of DC measurements, or its impedance in the case of AC measurements.

Theoretical description of rails in terms of current conductivity

In terms of conductivity, a pair of rails can be described as a passive circuit with distributed parameters. The following wave equations can be used to describe its behavior.

$$(1)\qquad \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & -Z_0 \sinh \gamma l \\ \dfrac{-\sinh \gamma l}{Z_0} & \cosh \gamma l \end{bmatrix} \times \begin{bmatrix} U_1 \\ I_1 \end{bmatrix}$$

$$(2)\qquad \gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

Where R is longitudinal resistance of a pair of rails per length unit, L represents their inductivity per length unit, C represents capacity per length unit and G represents leakage conductance.

In most cases, it is possible to use a more simple description. When measuring voltage drop on a segment that is several meters long, with frequencies ranging from zero to several hundred Hz, it is sufficient to consider one single rail as an element that has conductivity or impedance.

However, both the rail's resistance and its impedance are slightly different in different cases. There are several standardized rail sizes, but none of these types have identical parameters all the time.

Table 1. Most frequently used rail types in the Czech Republic

type	weight (kg/m)	cross-section (cm^2)	resistance (μΩ/m)
UIC 60	60	76,86	32,5
R 65	65	82,95	30,1
T	50	63,33	39,5
S 49	49	62,48	40,0

In the course of time, all rails get worn out, which reduces their cross-section, and consequently increases their resistance. Resistivity is also influenced by temperature. Steel has a temperature coefficient of resistance of approximately 0,005 K-1, which means that when temperature changes by 10K or 10˚C, resistance will change by approximately 5%. Depending on weather conditions, temperature of rails can vary by 40˚C or more, which means that their resistance can vary by more than 20%.

Situation is more complicated in the case of alternating current, because in this case it is necessary to consider impedance, not resistance. Due to the fact that rails are made of ferromagnetic materials, their inductivity is much higher than that of similar conductors that are paramagnetic, such as aluminum, or diamagnetic, such as copper. One of the factors influencing inductivity is the shape of the rail, and for this reason mechanical wear has to be taken into consideration as well. Since permeability of steel (and of all the other ferromagnetic materials) depends on magnetic field strength, inductivity depends on current magnitude. Of course, inductive reactance is frequency dependant.

Laboratory measurements of resistance and impedance of a rail segment

To verify the resistance of a rail segment, our team has performed laboratory measurements on a 1m long sample of UIC 60 rail. Both DC and AC measurements were carried out, AC measurements were for varying frequencies.

The following voltage sources have been used:

- controlled rectifier for DC measurements
- programmable three phase power source Pacific 3120-ASX and step down transformer (only one phase was used).

Our measuring system consisted of a clamp ammeter PROVA 2000, USB6210 AD converter, a laptop and software created LabVIEW.

Volt-ampere characteristics of a 1m long rail sample for DC current are shown in Fig. 1. Dependence between current and voltage is linear, and it has been found out that the 1m long rail sample has a resistance of 30μΩ.

AC measurements for 50Hz-650Hz have also been carried out. Examples of volt-ampere characteristics for some selected frequencies are shown in Fig. 2. This time, volt-ampere characteristics are slightly nonlinear, and it can be clearly seen that impedance is strongly dependent on frequency.

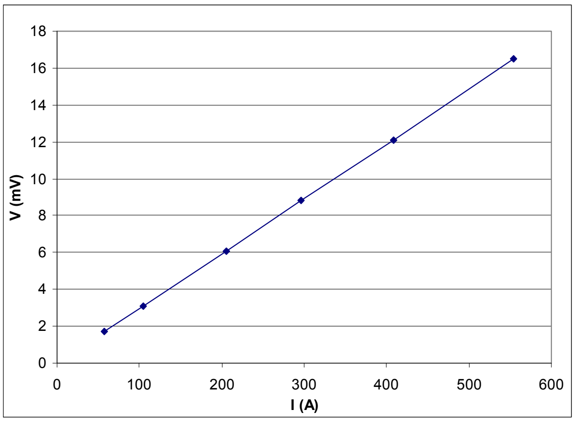

Fig. 1. DC volt-ampere characteristics of a 1m long rail

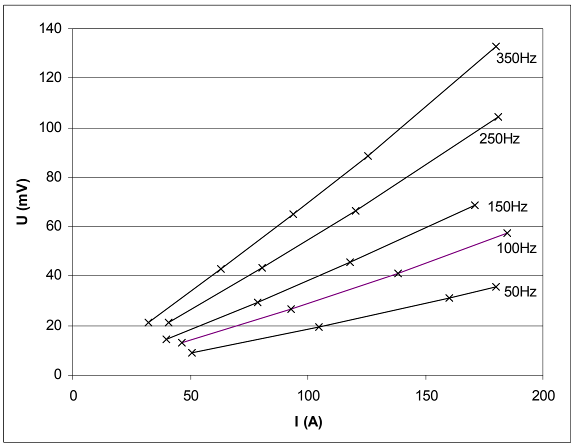

Fig. 2. AC volt-ampere characteristics of a 1m long rail sample for some selected frequencies

The dependence of impedance on frequency was determined for 100A current, including both its magnitudes and phase shift. Fig. 3. shows an equivalent circuit that was created in order to model measurement results.

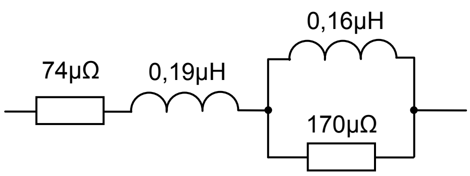

Fig. 3. Equivalent circuit for determining the impedance of a 1m long rail sample, valid for 50-650Hz frequencies

Impedance and phase shift measurement results as well as calculated values corresponding to the equivalent circuit are shown in Fig. 4. In this frequency range, differences between measurement results and calculated values do not exceed 4% impedance and 4˚ phase shift. The selected frequency range covers important harmonic components of currents flowing through rails in AC 50Hz traction. AC traction locomotives mostly draw the following harmonics: 1st (ideally, there would only be this harmonic), 3rd, 5th and 9th, corresponding to 50, 150, 250 and 350Hz frequencies respectively. Certain harmonics from this range can also be found in DC traction current. This type of traction is usually supplied by a 12-pulse rectifier (railways), or 6-pulse rectifier (trams), which corresponds to harmonic components 600Hz (50-12) or 300Hz (50-6). 75Hz or 275Hz frequencies can also be found in rails, because these frequencies are used in track circuits of train protection systems.

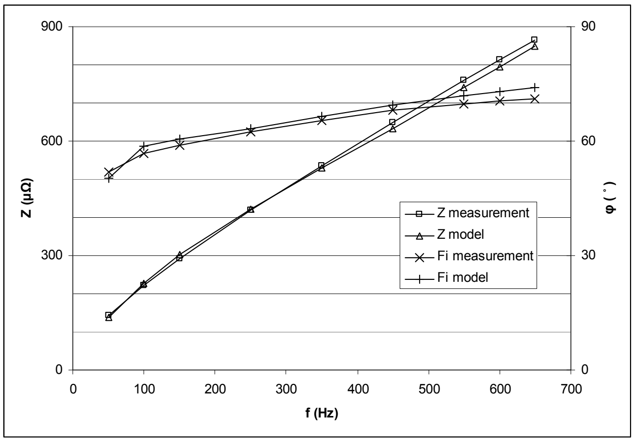

Fig. 4. Impedance and phase shift of a 1m long rail sample

Practical verification of using Ohm's method to perform current measurements on rails

If the impedance of rail corresponding to a certain frequency is known, it is possible to find out the amount of current flowing through the rail by means of voltage drop measurement. To verify this procedure, a measurement was performed on a railway track between the cities of Ostrava and Bohumín, in a place called Vrbice.

The railway track where our measurements were carried out is electrified by a 3kV DC system. Current was measured by clamp ammeter PROVA 2000, and results were recorded by a measuring system consisting of USB6210 converter, laptop and appropriate software. Sampling rate was 10kS/s. The diagram is shown in Fig. 5.

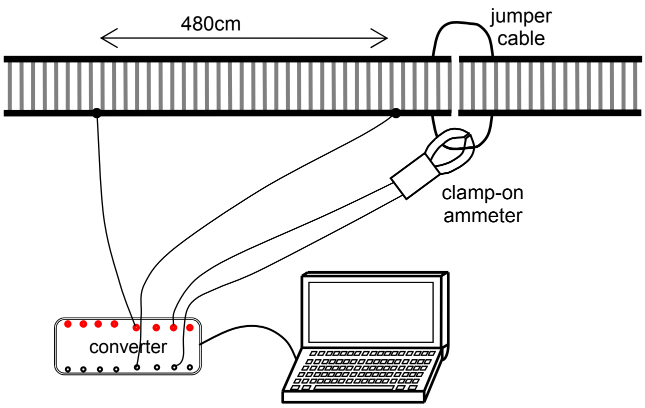

Fig. 5. Schematic diagram of measurement on a railway track

This measurement took approximately one hour. Over this period of time, only DC component (which was predominant) and a much less significant AC component 275Hz were captured. The 275Hz was the frequency of track circuit.

Figs. 6. and 7 show a comparison between current values measured by ammeter, and those calculated from voltage drop on the rail for the 4-minute time span when load was the most significant.

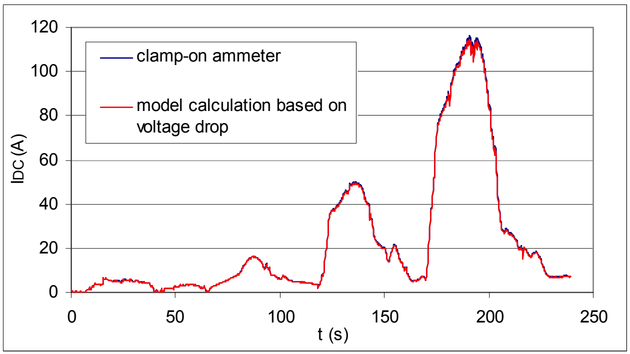

Fig. 6. DC component of current flowing through a rail, measured by clamp ammeter and calculated from voltage drop

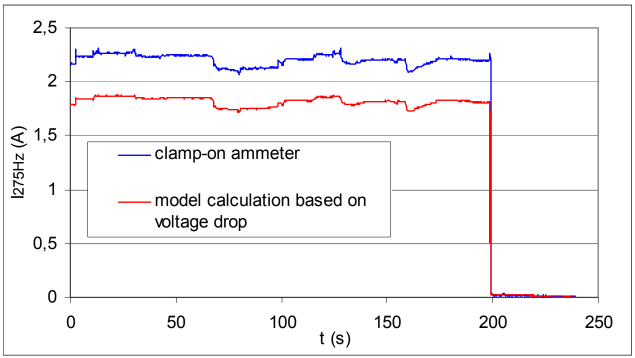

Fig. 7. AC component of current flowing through a rail 275Hz, measured by clamp ammeter and calculated from voltage drop

Based on the comparison of results obtained by both methods, it is possible to conclude that in the case of the DC component, results match very well. However, the disparity between both methods is much higher for the 275Hz component. Excluding those segments where measurement accuracy was low due to low current (i.e. less than 20A), both methods displayed an acceptable variation of approximately 2%, for the DC component. However, the value of the AC component 275Hz was much lower (approx. 2A), and for this reason measurement results were much more likely to reflect measurement errors, with a variation of approximately 17% during the whole measuring process. As far as phase shift of the 275Hz component is concerned, the model shows a shift of 63.9˚, while measurement showed 63.7˚ ±1˚, which is perfectly acceptable.

Conclusion

The method that our team has used to measure current flowing through rails is based on measuring voltage drop on a segment of a certain length. An equivalent circuit of a rail was created for 50-650Hz frequencies, as well as for DC current. Parameters of this equivalent circuit were determined on the basis of laboratory measurements performed on a 1m long sample piece of rail.

To practically verify the applicability of this model, measurements were carried out on a railway track equipped with a DC 3kV traction system. It was found out that current flowing through the rails contains a DC component and also a 275Hz component, which is the frequency of the track circuit. Measuring equipment included clamp ammeter PROVA 2000, used for current measurement, a 4.8m long segment of rail, a laptop and USB6210 converter, used for result recording. Current was calculated from voltage drop, based on a previously created model.

Measurement results obtained with the use of the clamp ammeter were subsequently compared with values that were calculated from voltage drop. In this way, it was found out that there is relatively little variation in the case of the DC component, as long as current values below 20A were not taken into consideration. This error for DC current was approximately 2%.

AC component 275Hz was always low, only approx. 2A. For this reason, relative measurement error was very large, around 17%. Variation of measured and calculated phase shift was ±1˚, which is a good result.

It was verified that the proposed method is applicable on DC current measurement.

Further measurements are needed to be able to determine the applicability of this method on AC current measurements. These measurements need to be performed on AC railway traction 25kV/50Hz. Here, AC current values, fundamental frequency as well as other harmonic components, are significantly higher, therefore the results obtained would be more revealing.

This work was supported by project MŠMT ČR KOTAKT II: LH 11125 and VSB-TU Grant SP2013/47.
The authors would like to thank for this support.

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