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Distributed Measurement System with GPS Synchronisation and Its Use in Electric Traction

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***Abstract*—This paper deals with distributed measurements in power electrical engineering. The word “distributed” means that the measurement is carried out simultaneously in different locations. Distance between these locations can be tens of kilometers or more. For a long time, the authors have been performing electrical measurements in electric traction, especially in electrified railways. Due to the extensiveness of the railway network, it is very important to find the solution of this problem. After a thorough examination of the subject, the authors have developed computer based measuring apparatuses and GPS based synchronizers. This paper describes the creation of the GPS synchronizer as well as a post-processing data synchronization method. The concluding part includes an example of this apparatus being practically used while carrying out measurements in a railway traction transformer substation and on track circuits. Some interesting measurement results, as well as their analysis, are also presented here.**

***Index Terms*—Electric variables measurement, timing, computerized instrumentation, global positioning system.**

I. Introduction

Our team deals with measurements in the area of power electrical engineering, especially electric traction, where dimensions of the circuit worked with may reach tens of kilometres. Sometimes, these measurements are distributed, i.e. a particular measurement is carried out in several places simultaneously, within a distance ranging from hundreds of meters to tens of kilometres. As computers are often used as digital waveform recorders, results are obtained in the form of several data files, each coming from a different location. For this reason, time synchronization comes as a necessity.

Different synchronization options have been analysed by our team, and some of them have been tested. In the end, a GPS based synchronization system was developed, with an accuracy better than 1 microsecond. This device has been used on various occasions.

The use of the synchronization system developed by our team brought some interesting results.

Distributed electrical measurements can be carried out in several different ways. Some of them are based on data being transferred online, either via a special cable (analog or digital signal), or with the use of Ethernet or the Internet, or wireless, for example Wi-Fi or ZigBee [1]. In the case of distances longer than one kilometre, the only option that remains applicable is the internet, since it is not possible to lay down a cable. The problem is that data transfer via the internet always has a certain latency, and internet connection is not available in some places [2].

Another option is to use independent measurement apparatuses that are time synchronized. However, it has to be kept in mind that if very precise synchronization is needed, internal clocks in computers (or other devices of that kind) are not suitable. They are based on quartz crystal resonance and their frequency tolerance is approximately 10 ppm [3], which means that a deviation of more than 1 second per day can occur. Therefore, some kind of wireless synchronization is needed. One option is to use radio signal (e.g. DCF77 for Western and Central Europe) or GPS (available worldwide). For DCF77, signal quality is not sufficient in some places and receiver accuracy ranges from 1 ms to 100 ms. On the contrary, GPS signal is available practically everywhere, its accuracy being several ns, but usually the receiver has to be located outdoors [4], [5]. Of course, there are more satellite navigation systems (Glonass, Galileo, Compass), but some of them have not yet been completed, and GPS receivers are easily available.

After experimenting with both DCF77 and GPS, our team have decided to use the latter as a base on which to develop our synchronization apparatus.

Time synchronization of measurements with the use of GPS has been investigated by various authors, e.g. [6]–[9].

Reference [6] contains a description the design, construction and testing of equipment for the calibration of distributed measuring systems. In this solution, however, exact time information for specific results, which the authors need, cannot be obtained.

Reference [7] describes a time base stabilization system, as part of a measuring system. This does not solve the problem of the synchronisation of two independent measurements, starting at different points. Nevertheless, it is a very interesting solution in terms of stabilizing the sampling rate of a measurement which is already running (see the final part of Chapter III).

References [8], [9] describe the construction of an apparatus for accurate time base generation, as well as for time stamping of measured events. As for time stamping, this solution is very similar to ours. However, the solution described in [8] and [9] is too complex for our needs, and it does not allow easy connection to existing measuring

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apparatus, as described in Chapter II.

For this reason, we chose our own solution, using really inexpensive components (the cost did not exceed 50 €). In spite of the low cost, this equipment fully meets the required accuracy.

II. Measurement Synchronization Method and Synchronization Apparatus

For our measurements in the area of power electrical engineering, we usually use computers, which are equipped with an AD converter and corresponding software, thus the computer works as a multichannel digital recorder [10]. Usual sample rate is 10 kS/s (can vary from 100 S/s to 40 kS/s). Measuring software stores obtained data into files, creating a new file every hour. An extra channel was added on the recording device to record synchronization signal from the GPS receiver. Time accuracy for 10 kS/s can be 0.1 ms. In the data processing phase that follows data acquisition, records from several measuring computers are put together, in order to match synchronization signals from different receivers.

The GPS-610F module that was used as a receiver here provides two outputs, a serial output with text strings containing information about position and time (so-called NMA sentences [11]) – not accurate enough to make required synchronization possible, and a TTL output called 1 PPS (1 pulse per second), where a pulse with a very accurate rising edge occurs every second. According to documentation provided by manufacturer, the accuracy is 300 ns. These two signals are further processed by means of a microcontroller.

This microcontroller receives text strings through serial port, plus signal from the 1 PPS that is connected to the microcontroller's external interrupt input. With the completion of each minute, for example 13:48:00, the microcontroller waits for a next interrupt from 1 PPS. On receiving an interrupt, the microcontroller immediately generates a pulse on the output. This pulse is positive for minutes 1–9 and negative for minutes which end with a zero. This makes it very easy to identify every minute and every 10 minutes.

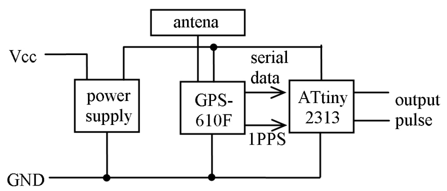

Fig. 1. Simplified schematic diagram of the synchronization device.

In this particular case, ATtiny2313 microcontroller was used, with clock frequency being 4 MHz (clock signal period being 250 ns). Overall accuracy of the synchronization device can be determined based on clock frequency and GPS-610F accuracy. Some microcontroller instructions take 1 clock period, others take 2 periods (250 ns or 500 ns). This means that after receiving an interrupt signal, the microcontroller starts to execute an interrupt within 0 ns–500 ns. In this way, total accuracy of an output synchronization pulse is 300 + 500 = 800 ns. This accuracy was verified by measurement, where output pulses from two synchronization devices were compared with the use of a two-channel oscilloscope, and the difference between them never exceeded 800 ns.

Figure 1 shows a simplified schematic diagram of the synchronization device. Supply voltage of the device is 5 V–7 V, usually coming from a computer USB port.

III. Data Processing Phase

Specialized software was created in the LabVIEW system to make it possible to join data files created by various measuring devices during a certain period of time. All data files start with a header containing general information concerning the measurement in question (i.e. number of channels and sampling frequency), as well as information concerning these channels (name and multiplicative constants). After the header comes a two-dimensional array with measured values of the individual channels in time (16-bit integers). This software makes it possible to join up to four such files in “parallel”, i.e. as if they were created on one device. At the same time, it is possible to manually set the shift of individual files, so that GPS synchronizer marks match. Record length is usually 1 hour per file. Figure 2 shows front panel of this software.

Figure 2 shows an example of joining 3 data files (there may be 2 to 4 of them). Each window displays the preview of the record of one file. The person operating the system manually searches the record, to find the synchronisation pulse from the GPS synchroniser, and sets the cursor (the yellow vertical line) at the beginning of this pulse. This is done for all the joined files. Then, clicking on the icon starts saving the joined data in a single output file.

Unfortunately, it was found out that even if records are synchronized at the beginning, a shift can occur over time. This shift is caused by the inaccuracy or instability of crystal oscillators in AD converters [12]. Deviation for 1-hour recording can be up to 30 ms, i.e. 8.3 ppm, which is still within the accuracy range of common crystal resonators. For some purposes, a 30 ms error is not a problem, but for other ones higher accuracy is needed. Whenever it is necessary to evaluate phenomenons within one period of power network, a 30 ms error is unacceptable, as it represents 1.5 period (for 50 Hz frequency), or when evaluating phenomena happening in the range of milliseconds [13], [14].

An ideal solution of this problem would be to control oscillator frequency in the AD converter according to [7]. However, that is rather complicated and since the converters that we use are commercially produced, it would require extensive adjustments in their construction. For this reason, we have chosen the software solution, i.e. a simple sample rate conversion of the measured data file.

For this reason, a new version of the joining software was created. This new version performs the same activities as the previous one, plus it automatically synchronizes recordings every minute, according to GPS synchronizer marks. The first file recorded is taken as a “master file“, while all the following files are subordinate to it, i.e. adjust to this first file. Every minute, the software searches in the files for the synchronization pulse rising edge.

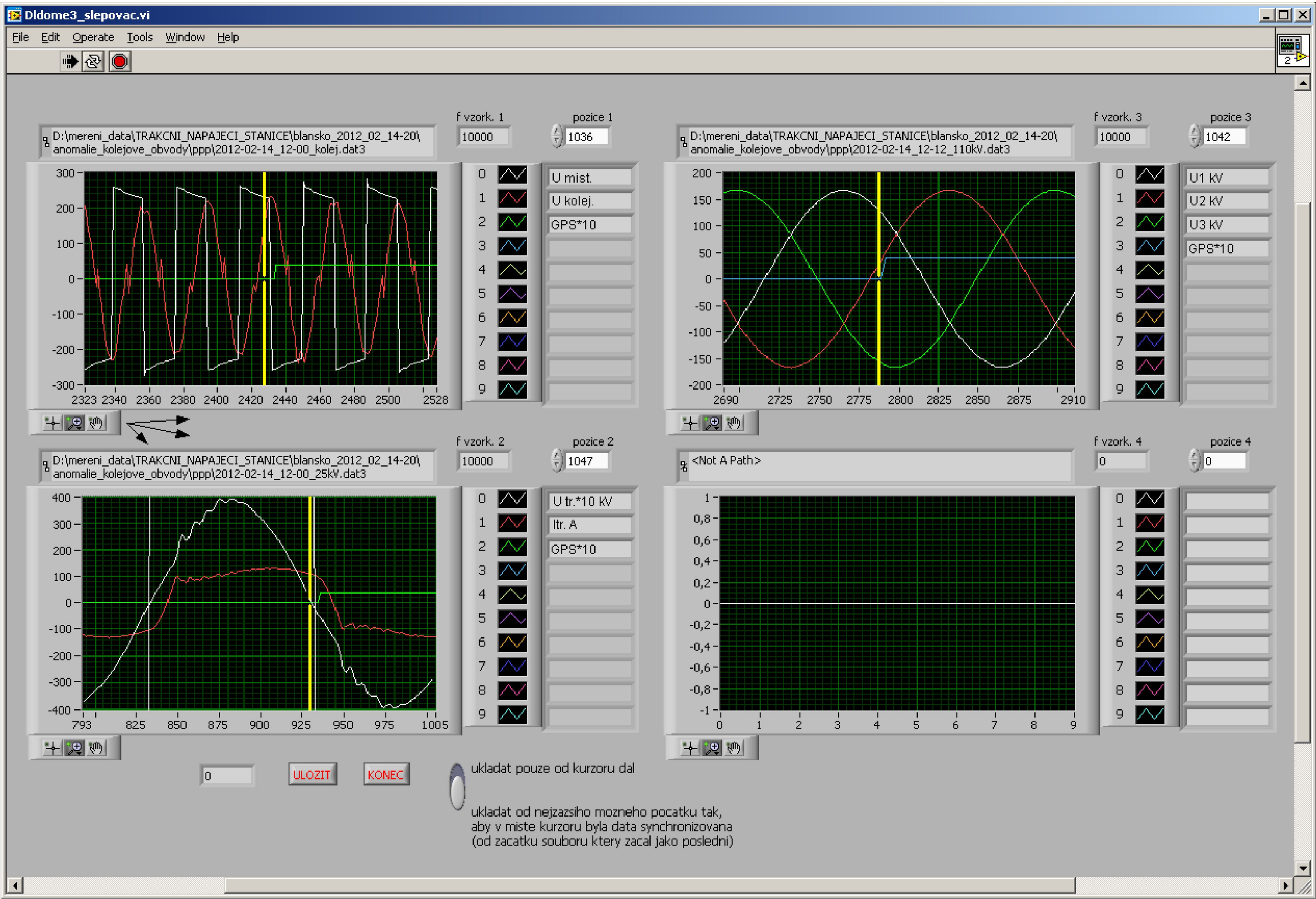

Fig. 2. Software for data joining.

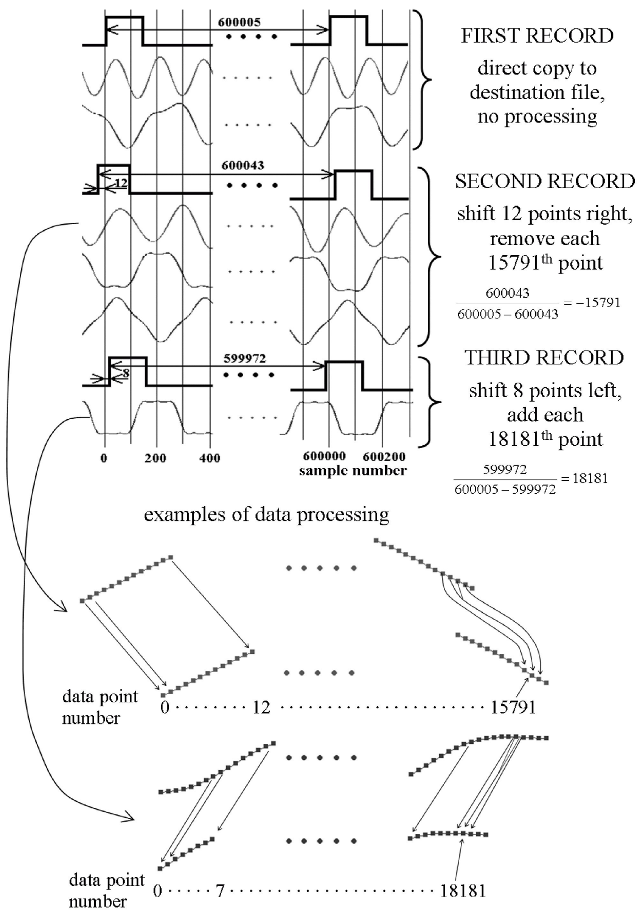

Fig. 3. Principle of data processing.

The channel containing synchronization signal for each file is set manually. If synchronization pulse shift of individual records exceeds 2 ms per minute, the software reports an error because it means that something went wrong in the course of the measurement process. If all synchronization pulses are found within the 2 ms range, the number of samples by which subordinate files have to adjust is calculated. That means that records in these subordinate files must be prolonged or shortened, depending on whether they were too fast or too slow. This could be done with the use of the “Resample” function in LabVIEW. However, the number of samples that need to be processed in this way is very small (1 out of 30 000 at the most), and so a different method was selected. Whenever it is necessary to deduct a sample, two neighbouring samples are substituted with a single sample calculated as their average. Whenever it is necessary to add a sample, a new one is inserted between two neighbouring samples, calculated again as their average (Fig. 3).With this improved algorithm, error of the resulting file after synchronization never exceeds 0.1 ms (sample rate being 10 kS/s), which, with a 50 Hz frequency, represents a 1.8° phase shift.

So far, the above mentioned error (synchronization pulses following one after another being more than 2 ms apart) has never occurred.

IV. DESCRIPTION OF THE TRACTION TRANSFORMER SUBSTATION AND TRACK RELAY SUBSTATION

The following part shows an interesting phenomenon recorded at the traction transformer substation and track relay substation.

Traction transformer substation feeds the 25 kV/50 Hz AC traction. Its most important part is a single phase 110 kV/25 kV transformer with a rated power of 12,5 MVA. 25 kV voltage is used to feed the contact line. Since single-phase AC traction units generate adverse current harmonics, the traction transformer substation is equipped with a filtration-compensation device that helps minimize the penetration of current harmonics into the power network [15]. This filtration-compensation device is formed by L-C filters, mostly 3rd and 5th harmonics filters. Simplified scheme of this traction transformer substation is shown in Fig. 4. Said filtration-compensation unit does not limit the magnitude of current harmonics in contact lines and rails.

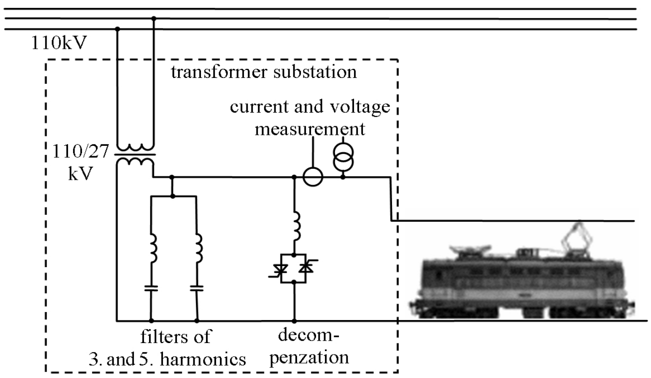

Fig. 4. Simplified scheme of traction transformer substation.

Rails serve as traction current conductors as well as track circuit conductors. Track circuits detect the clear or occupied condition of a specific track section and therefore are very important in terms of rail traffic safety. The most frequent case is the so-called double rail track circuits (shown in Fig. 5) [16]. Small AC voltage is led in between the two rails by an impedance bond (transformer). This voltage is detected by a second impedance bond, located on the opposite side of the rail section. The oldest track circuit voltage evaluation device is the track relay (see Fig. 5).

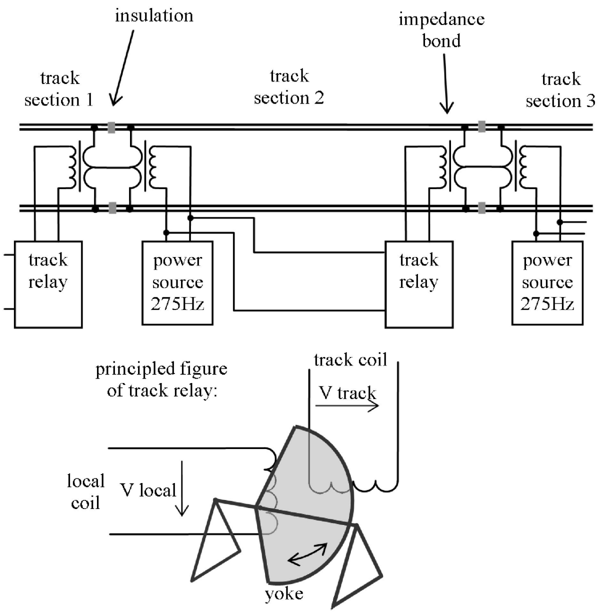

Fig. 5. Track circuit with track relay.

When there is a train present on the monitored rail section, voltage is short-circuited, which is a signal that this rail section is occupied. Following voltage on "rail coil" of the track relay falls to zero, the yoke drops off automatically due to gravity and the relay signalizes that the rail section is occupied. Rail circuits operate at a frequency that is not found in the traction circuit. Otherwise interferences might occur [17]. The most commonly used frequencies are 75 Hz and 275 Hz. In cases where traction units might generate the above mentioned harmonics, they must be equipped with efficient filters to eliminate these frequencies [18].

V. Measurement in Traction Transformer Substation and Track Relay Substation

In the event of an incorrect or insufficient function of traction circuit filters, track circuit functioning might be influenced by traction current harmonics. In the case of only insignificant interferences, this influence does not necessarily lead to dangerous track circuit failure, however it may be noticeable when track relay coil voltage is measured. In past years, our team has carried out several measurements on track circuits and in traction transformer substations, looking for evidence of mutual interference. The measurement described below was carried out in Blansko, on February 14th–20th 2012. Traction transformer substation and relay substation are located approximately one km away from each other, track circuits operating at a frequency of 275 Hz. Voltage and current on the contact line were measured in the traction transformer substation. Voltage on both coils of the track relay was measured in the relay substation. Each measurement was carried out with the use of one laptop computer equipped with an analog to digital converter, with a sample rate of 10 kS/s. All acquired data were saved. Both measurements were GPS-synchronized. This was followed by a harmonics analysis of the obtained data, which showed that there was not a single case registered of a dangerous interference between track circuit and traction current. Nevertheless, certain interesting phenomenon were detected, where the waveform of voltage on "rail coil" of the track relay was influenced by interferences between traction current and track circuit source waveform (these waveforms are shown in Fig. 6). If the falling edge of 275 Hz source voltage coincides in time with traction current, the peak of track relay voltage on "track coil" is higher than usual. If the falling edge of source voltage coincides with traction current in opposite direction, the peak is lower than usual.

This phenomenon is visible, nevertheless it has no effect on harmonic spectrum at the 275 Hz frequency. Therefore, it does not threaten the functioning of the track circuit. This phenomenon was discovered thanks to the use of the above mentioned GPS synchronizing device.

The reasons why this phenomenon occurs are rather complex and their investigation would require detailed measurements at different points of the traction circuit, followed by in-depth analysis. Here is a brief explanation, based on known data.

In the circuit shown in Fig. 6, if traction current is divided symmetrically between both rails, traction current has no influence whatsoever on voltage in the rail circuit.

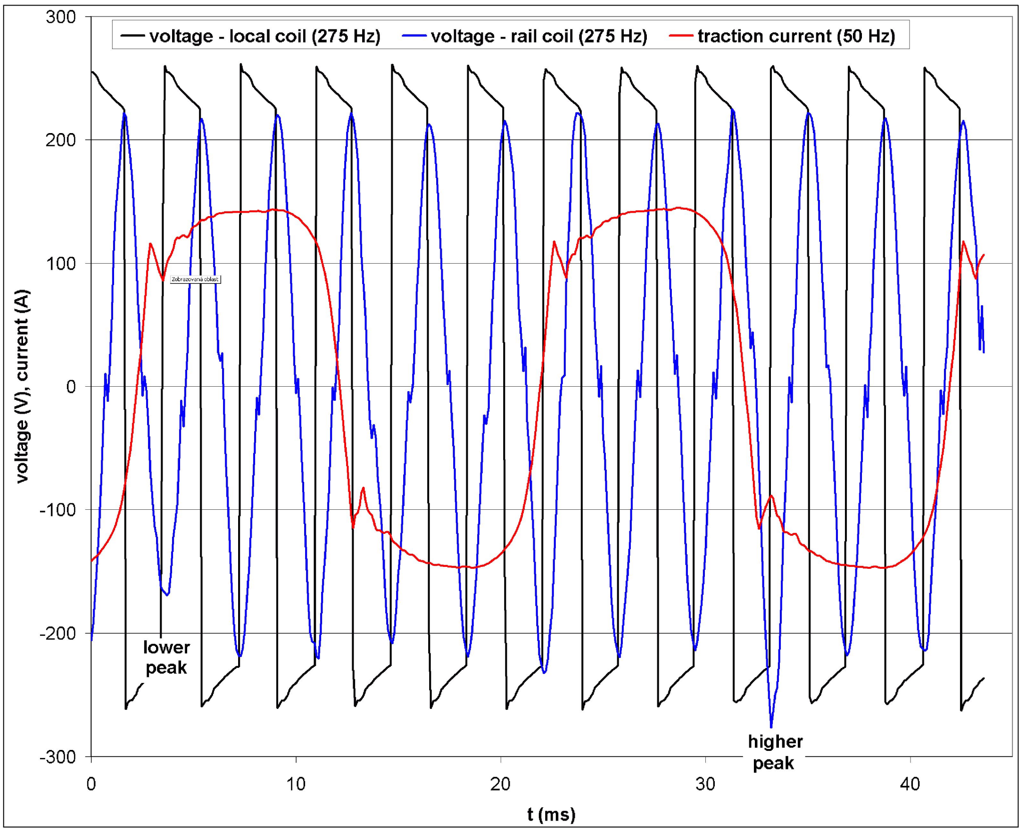

Fig. 6. Example of results of distributed measurement in traction transformer substation and in track circuit.

That is the ideal state. In reality, however, greater or smaller asymmetry always exists. This asymmetry is caused especially by unequal contact resistances of rail jumpers. Moreover, asymmetry depends on frequency (it is greater for the higher frequencies - harmonic components f > 50 Hz), which is caused especially by locomotive chassis reactance.

If there are unequal amounts of traction current flowing through both halves of the impedance bond, unwanted voltage is induced in secondary winding. For the above mentioned reasons, this phenomenon is also frequency dependent.

Available circuit element parameters (see Fig. 6) have been used to create a simplified substitution diagram, which was inserted into a simulation program (Microcap 9).

This diagram in the simulation program is shown in Fig. 7.

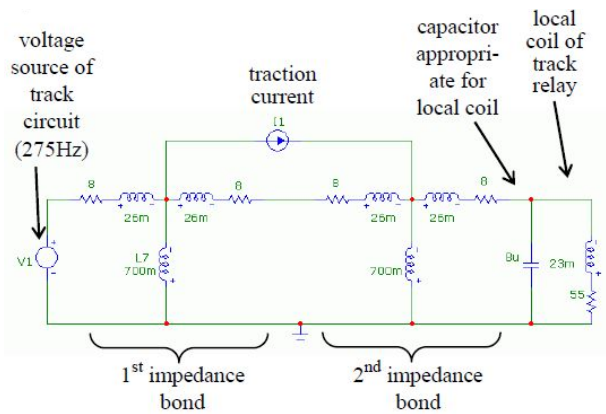

Fig. 7. Substitution diagram for computer simulation.

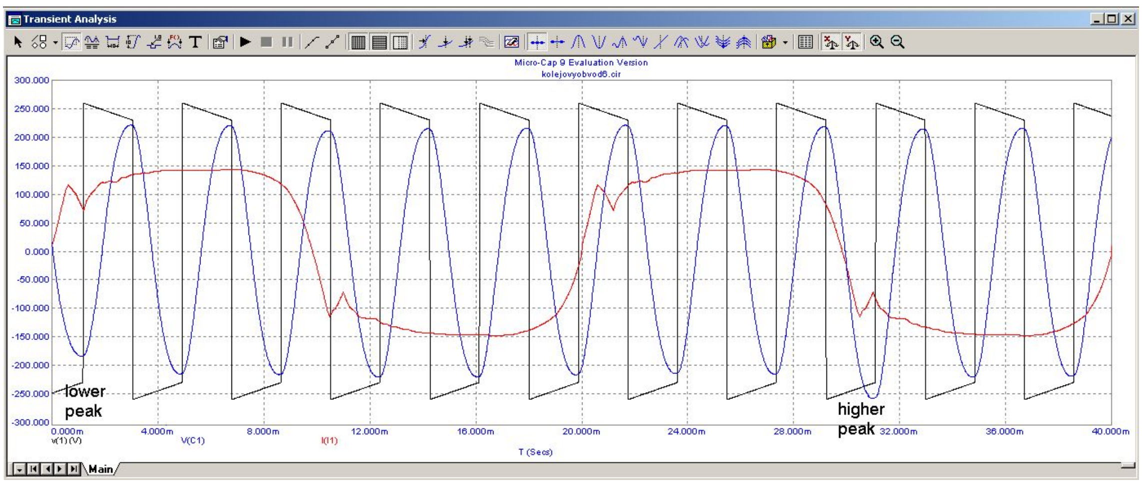

Fig. 8. Results of computer simulation.

Values of the elements in the substitution diagram were taken from [19] and [20], or estimated based on information from these sources. Rail impedance and connecting cable parameters were not considered. The result of the simulation is shown in Fig. 8.

As seen in Fig. 8, simulation confirmed the occurrence of higher and lower voltage peaks on the local track relay coil. As certain parameters have been omitted, the simulated waveform does not include small glitches of this voltage around the zero value. (These are probably caused by the impedance and capacity of cables, which are not known, and therefore were not taken into consideration).

VI. CONCLUSIONS

The GPS based synchronization device that this paper deals with was created with the aim to time synchronize distributed measurements, in the area of power engineering. Up to date, this device has been used to carry out various electric traction measurements. This paper describes measurements in traction transformer substation and a relay substation Blansko (AC electric traction 25 kV/50 Hz) where track circuits operate at a frequency of 275 Hz. An interesting phenomenon was discovered thanks to the use of this GPS based synchronization device, where, under certain circumstances, interference occurred between traction current and track circuit voltage. However, this interference had no effect on 275 Hz frequency, and therefore was not dangerous for track circuits and would probably go unnoticed, had it not been for our GPS synchronized measurement.

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