Regulated Electric Drainage and its Interference with Track Circuits

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Abstract. *Electric drainage is a power electronic device used to protect underground metal devices (such as piping) from the corrosive effects of stray currents. Stray currents are usually caused by DC electric traction, such as trams or railways. In places where stray currents leave the underground device and return into rails, they cause significant electrochemical corrosion of buried devices. The principle of electric drainage is based on electrical connection between the underground device and electric traction rails, which ensures that current flows through this connection, instead of flowing into the ground. Nowadays, the most widely used type is regulated electric drainage, where current is regulated by means of Pulse Width Modulation (PWM). Because of this modulation, current flowing through the drainage contains harmonic components with different frequencies. In modern railways, track circuits are often used as an important part of the track security system. For safe operation, it is necessary to ensure that frequencies generated by the drainage do not interfere with track circuits. This paper describes the design of a regulated drainage control system, with regard to its compatibility with track circuits and this paper contains related computer simulations and discussion of the results.*

Keywords

Current harmonics, electric drainage, electromagnetic compatibility, track circuits.

1. Introduction

In railway and tramway electric traction, rails serve as conductors which conduct electricity. Since rails are never perfectly isolated, some current leaks into the ground and flows through it. That is how stray currents originate. Trolleybuses and electric cars do not use rails as conductors, so they do not generate any stray currents. Stray currents contribute to the corrosion of metal objects buried in the ground (for example pipelines). Stray current corrosion may be far greater than simple galvanic corrosion [1]. From this point of view, the most critical part is so called anode area (see Fig. 1) [2]. Electric drainage can protect the anode area of an underground device.

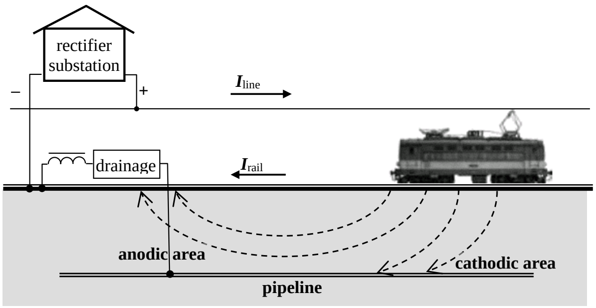

Fig. 1: Stray currents and electric drainage connection.

The most advanced type of electric drainage is regulated electric drainage. It conducts current only in one polarity, as a diode. In addition, it is able to regulate the current when it is too high or when the potential of the underground device reaches higher negative values (which is undesirable due to the release of hydrogen and metal embitterment). Regulation is usually controlled by a PI or PID controller. There are also adaptive regulation and self-learning solutions [3].

Current regulation is usually based on Pulse Width Modulation (PWM). However, PMW generates current harmonics of different frequencies. When drainage is installed on a railway track equipped with a track circuit, current harmonics must not interfere with the frequency of this track circuit.

Electric regulated drainage, which is currently being developed by our team, is going to be used on tram tracks. Due to future compatibility, it needs to be designed in a way that it is compatible with track circuits.

On tracks without track circuits, drainage is connected directly between rails and the underground device. Contrary, in the case of tracks with track circuits, inductors with an inductance of 20–40 mH are used to connect the drainage.

2. Track Circuits and Reserved Frequencies

The following three frequencies are used in track circuits in the Czech Republic: 50 Hz (slowly coming out of use), 75 Hz, and 275 Hz. Standard CSN 342613 specifies basic technical requirements regarding track circuits. Moreover, it defines protective frequency bands and security limits of current values for both analogue and digital track circuit receivers. Analogue receivers are more sensitive to interference, and so their security limits are stricter This means that if drainage meets the requirements for analogue track circuit receivers, it will also be compatible with digital receivers. Protective frequency bands and current limits are shown in Tab. 1.

Tab. 1: Protective frequency bands and current limits for track circuit receivers, CSN 342613 ed.2.

Protective frequency band (Hz)	**analogue receiver**		**digital receiver**
	duration		permanent
	permanent	<0.52 s	
44–54	0.26 A	0.50 A	1 A
68–80	0.11 A	0.50 A	1 A
262–280	0.13 A	0.50 A	1 A
	For, t<0.12 s, current is not limited.		For, t<1 s, current is not limited.

PWM frequency for drainage must be set outside the protective frequency bands listed in Tab. 1. If this condition is met, there should be no interference between drainage and track circuit. But the reality can be different.

- If there is another frequency in the circuit (from another source, for example from traction vehicle), these frequencies mix and if there is a non-linear component in the circuit, new frequencies (called heterodynes) are created, according to Eq. (1) [4].

  $$f_h = k \cdot f_1 + l \cdot f_2, \tag{1}$$

  where f_h is the newly created frequency, f_1 and f_2 stand for the original frequencies in the circuit. In this case, one of these frequencies is drainage PWM frequency, while the other one comes from another source. k and l coefficients are always integers.

  Usually, k and l coefficients are the most important. If $f_1 > f_2$, Eq. (1) becomes:

  $$\begin{aligned} f_{h1} &= f_1 + f_2, \\ f_{h2} &= f_1 - f_2. \end{aligned} \tag{2}$$

  Regulated drainage behaves just like a diode – conducts current only in one direction. For this reason, there is always a nonlinear component in the circuit. But this nonlinearity of the drainage occurs only when current changes its polarity (it is close to zero). When current value is close to zero, drainage does not regulate current, and consequently, there is no PWM.

- When the drainage changes the PWM duty cycle, especially if these changes occur repeatedly. This phenomenon is similar to amplitude modulation. This situation is common during operation, so it is necessary to control this kind of interference.

3. Drainage Control Algorithm

The authors of this paper are working on the development of a new prototype of regulated electric drainage. Previous steps of drainage development were described in [2] and [5].

After examining of several different possibilities [5], 100 Hz was chosen as PWM frequency. The duty cycle is going to be controlled in 16 steps, from 0 % to 100 %. Twelve consecutive PWM periods form one control cycle, after which recorded current and potential values are evaluated and PWM duty cycle is adjusted if necessary (see Fig. 2). The regulation cycle will be formed by 12 periods for 100 Hz PWM.

Control algorithm of regulated electric drainage changes the duty cycle between two consecutive control cycles only by one step (if necessary). For example, the following changes may occur:

$16:0(100\ \%) \rightarrow 15:1(93.75\ \%) \rightarrow 16:0(100\ \%) \rightarrow 15:1(93.75\ \%)\ldots$
$10:6(62.5\ \%) \rightarrow 9:7(56.25\ \%) \rightarrow 10:6(62.5\ \%) \rightarrow 9:7(56.25\ \%)\ldots$
$2:14(12.5\ \%) \rightarrow 3:13(18.75\ \%) \rightarrow 4:12(25.0\ \%) \rightarrow 5:11(31.25\ \%)\ldots$
$15:1(93.75\ \%) \rightarrow 14:2(87.5\ \%) \rightarrow 13:3(81.25\ \%) \rightarrow 12:4(75\ \%)\ldots$ Etc.

Computer simulation was done for a number of sequences similar to those mentioned above. It was found out that the limits listed in Tab. 1 are exceeded only when the PWM duty cycle changes gradually in several steps [5]. When duty cycle changes periodically

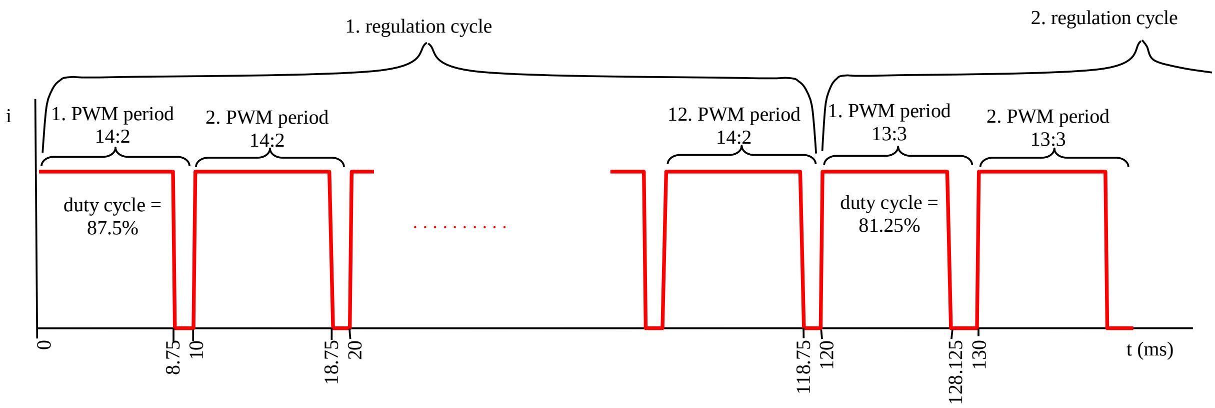

Fig. 2: An example of PWM regulation and its changes in time.

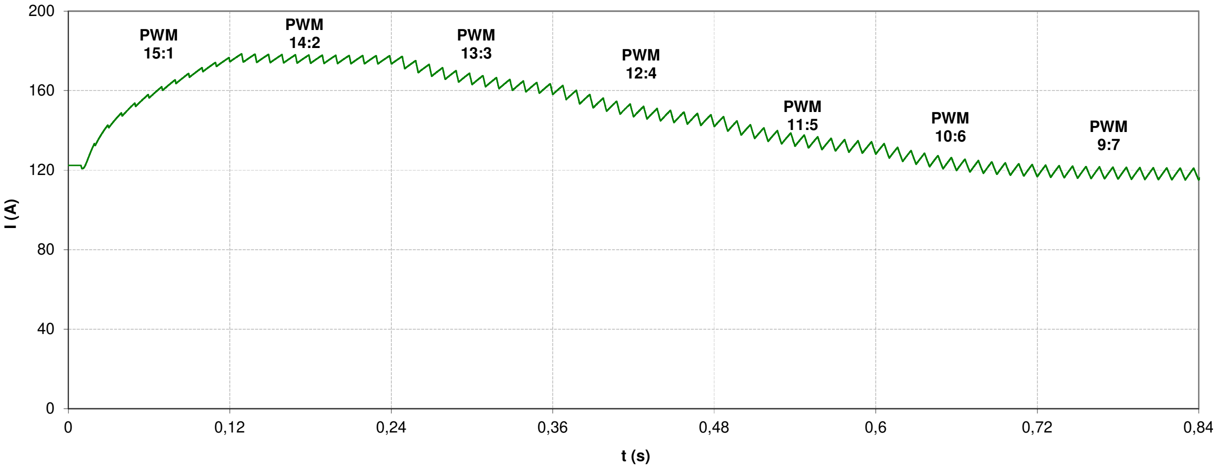

Fig. 3: Non-periodic changes of current as a reaction of drainage regulation to an increase in current consumption by a traction vehicle.

there and back, the limits for harmonics are not exceeded. For this reason, it is necessary to further focus on cases when duty cycle changes gradually, e.g. as shown in Fig. 3. In practice, such gradual changes in PWM duty cycle occur when current consumption of a traction vehicle increases rapidly and is followed by an increase of current. The control circuit of the drainage reacts by changing PWM duty cycle. Similar changes in current were recorded many times during our measurements.

4. Computer Simulation of Harmonics

The simulation was carried out in the Microcap software. The circuit diagram is shown in Fig. 4. Due to the current rating of the inductor which is connected in series to the drainage on the railway, current flowing through the drainage should not exceed 100 A. This must be ensured by the drainage regulation.

Simulation was performed for a value slightly higher than 100 A, approximately 120 A. To keep the simulation simple, the traction vehicle was represented by a resistor (R1 in Fig. 4). The 3 Ω value corresponds to a power of 3.6 MW. Immediate changes in current values can be achieved by changing the value of this resistor in the course of simulation, using a time-controlled switch (not shown in Fig. 3).

The selected value of the inductor between drainage and rails was 25 mH, in reality it is between 20-40 mH. The rail - crosstie - soil - piping circuit was replaced by a cascade of series-parallel combinations of resistances and inductances. In this model, inductance and resistance values were estimated based on standards and experience from previous measurements.

During the simulation, many PWM switching diagrams were investigated and aggregate RMS values of harmonics in protective frequency bands were evaluated according to Eq. (3):

$$I_{RMS-TOTAL} = \sqrt{\sum_{f=f_1}^{f_2} I_f^2}, \qquad (3)$$

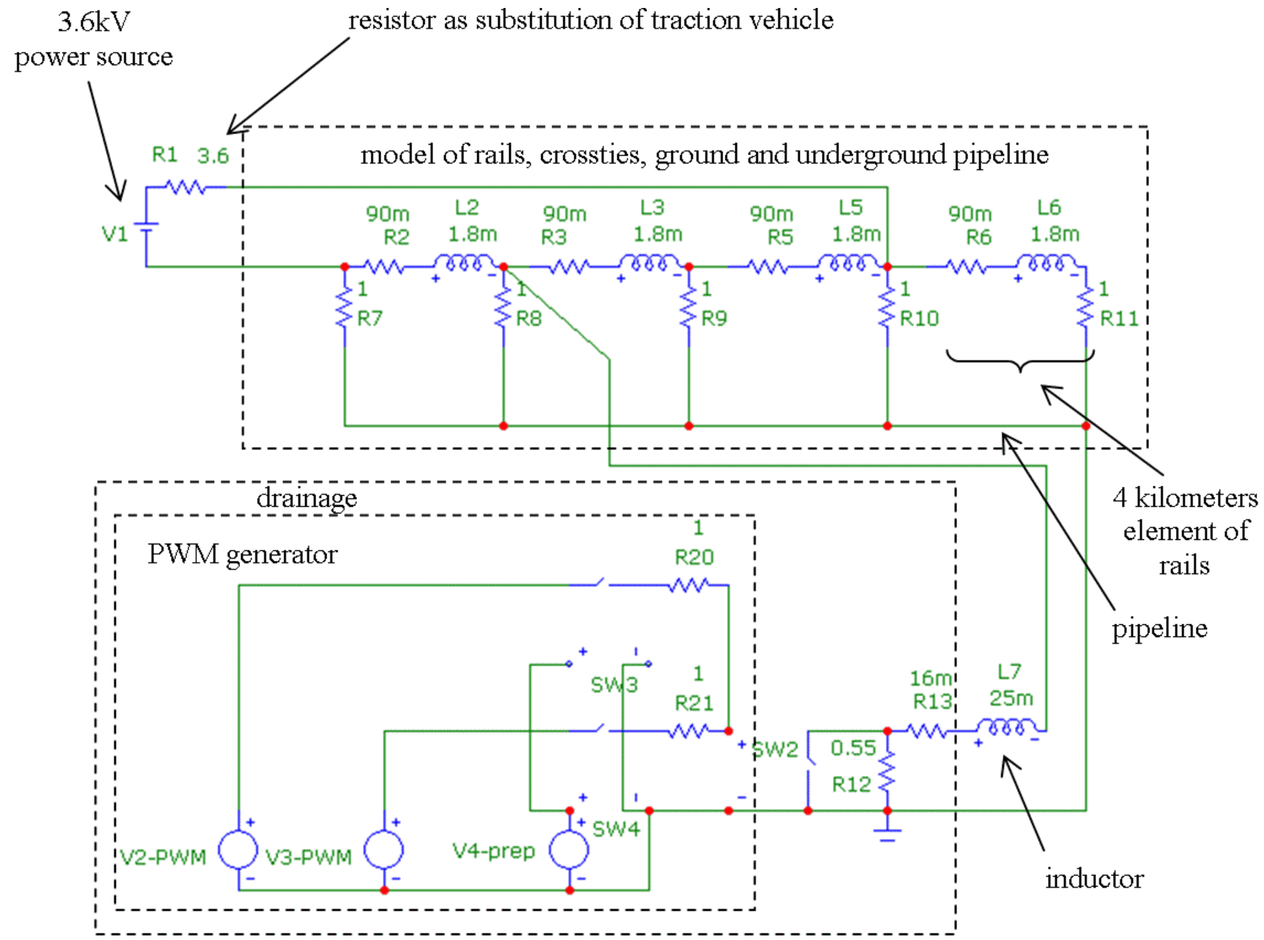

Fig. 4: Model created in the Microcap simulation software.

where I_f is the RMS value of a particular current harmonic with frequency f, and where f_1 and f_2 represent the lower and upper frequency of the protective frequency band.

Based on previous simulation results, a suspicion arose that the current harmonics which exceed the limits in Tab. 1 do not originate in PWM switching frequency, but they come from the shape of the current wave itself. This means that frequency change would not affect these harmonics anyway. For this reason, a simulation of the current harmonic spectrum was performed (shown in Fig. 3), as well as a simulation of a similar current wave composed of several lines, i.e. without PWM. These waveforms are shown in Fig. 5 and both of their harmonic spectrums are presented in Fig. 6.

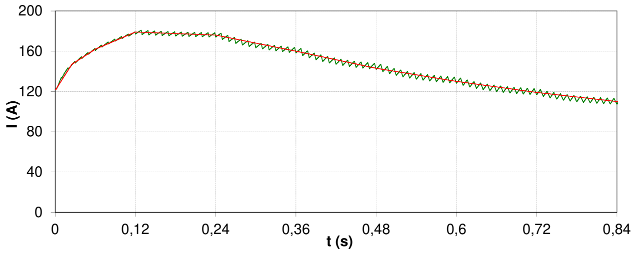

Fig. 5: Current wave generated by PWM and a similar current wave composed of several lines.

It is obvious from this figure that the harmonic components of both waveforms vary only near the 100 Hz, 200 Hz, and 300 Hz frequencies, i.e. near multiples

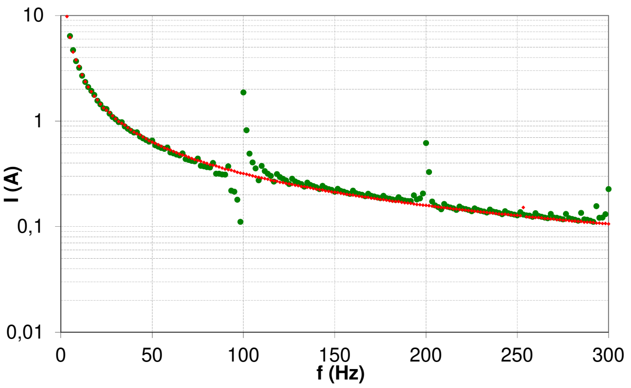

Fig. 6: The harmonic spectrum of the waveforms from Fig. 5. This spectrum was created for the time interval 0.12-0.72 s.

of the PWM frequency (100 Hz). For other frequencies, including track circuit protection bands, they are almost identical (Tab. 1). To eliminate undesirable frequency components, it is necessary to change the shape of the current wave, not just PWM frequency.

It has been suggested by the authors to compare the harmonic components of the waveform in Fig. 3 and the waveform in Fig. 7, where current regulation is faster. The CSN 342613 Standard states limits for harmonics for time intervals shorter than 0.12 s (unlimited), as well as for 0.12–0.52 s (0.5 A for all PWM frequency bands) and for time intervals longer than 0.52 s (different for each PWM frequency band, see Tab. 1). For this reason, the harmonics were evaluated using the sliding time windows of 0.12 s and 0.52 s length, which were moving along current waveforms, as shown in Fig. 8.

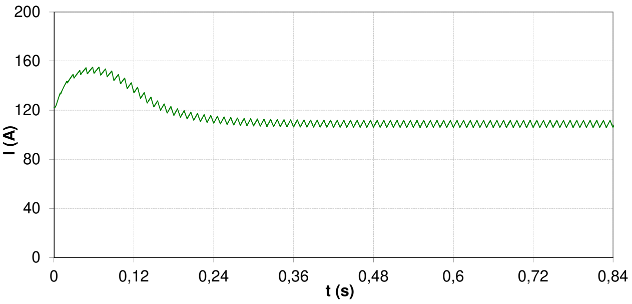

Fig. 7: Current wave for a 20 ms regulation cycle in reaction to the same increase in traction vehicle current consumption as in Fig. 3.

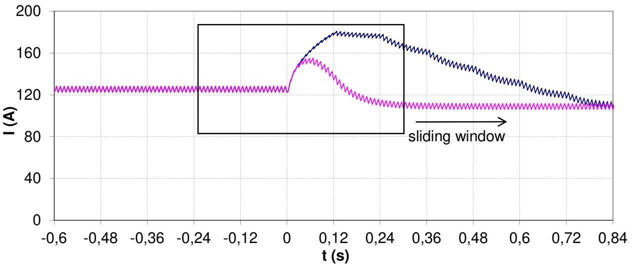

Fig. 8: Simulated current waveforms with the sliding time window in which Fourier analysis is performed.

Simulation results are shown in diagrams in Fig. 9, Fig. 10 and Fig. 11.

To be able to evaluate the influence of the regulation cycle length on the generated harmonics in Diagrams 9–11, it is necessary to compare values for the same sliding window length and for both regulation cycle types (both 120 ms and 20 ms), i.e. the thick blue curve needs to be compared with the thick red curve and the thin blue curve with the thin red curve. In all cases, the simulation results show that using the 20 ms regulation step leads to a decrease of harmonics in protective frequency bands.

For the values to correspond to CSN342613 Standard requirements, values for the 120 ms sliding window should never exceed 0.5 A. For the 520 ms sliding window, the values which are presented in Tab. 1. These values have been exceeded. However, it has been proved by simulation that shortening the regulation cycle leads to a decrease in harmonics, so in terms of future development, it is a good idea to follow this direction.

5. Conclusion

Based on previous simulations and measurements which were done in the process of developing regulated electric drainage, it was necessary to solve problems related to undesirable harmonic components generation during certain transient actions. These harmonic components are unacceptable when the drainage is installed on the railway, which is equipped with track circuits. For these cases, the limits for harmonics are stated by Standard CSN342613. It was found out that under certain operation conditions, the current solution does not comply with these regulations. Computer simulation of harmonics was done for different regulation speed (120 ms and 20 ms regulation cycles). It was found out that shortening the regulation cycle has a positive influence on current harmonics because it leads to their decrease. Even though the requirements stated by the standard are still not met, the decrease in harmonics value has been notable, so this is one of the ways which may be followed in further development of the drainage.

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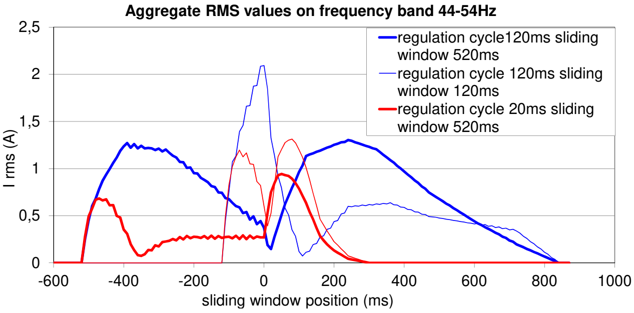

Fig. 9: Total effective values for the transient action shown in Fig. 8, for the 44–54 Hz frequency band.

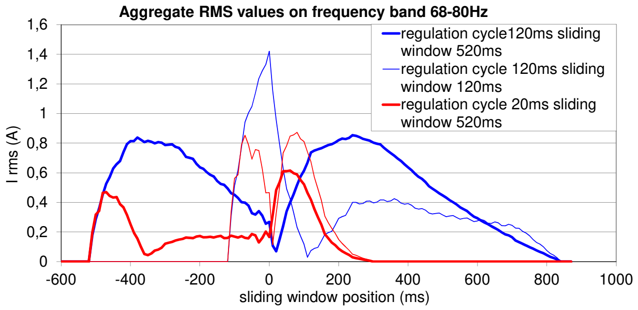

Fig. 10: Total effective values for the transient action shown in Fig. 8, for the 68–80 Hz frequency band.

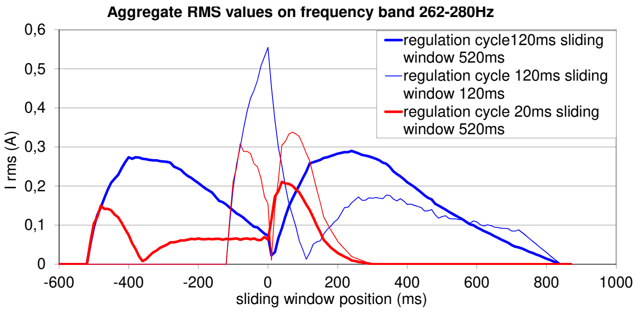

Fig. 11: Total effective values for the transient action shown in Fig. 8, for the 262–280 Hz frequency band.

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