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A New Design for Audio Frequency Track Circuits using Rail Resistance in Oscillator

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ABSTRACT

In the railway industry, track circuits are of great significance to ensure safe transportation and avoid crashes and accidents. These circuits majorly determine the existence of a train on sections of rail path called tracks using the conductivity properties of rail steel as a part of the circuit. In this paper, the problem of high implementation costs and blind spots for audio frequency track circuits is considered and solved. As the novelty of this work, a new structure for frequency track circuits is proposed leading to the elimination of all on-rail receivers and precise train positioning. The rail resistance is taken into account in the transmitter circuit to affect the amplitude of signals based on the traveled path. Moreover, a new topology is suggested to amend the audio frequency track circuit in order to decrease costs and remove blind spots as well. Compared to other track circuits, the proposed method has the advantage of lower costs, and train's location approximation without the use of GPS (global positioning system). The proposed method works with signals with frequencies within 80 to 180 Hz and the maximum length of track sections is set to 900 meters to restrict rail's resistance effects. Finally, in the simulation section, the efficiency of the proposed method is studied, and its capability is proved.

1. Introduction

Train detection systems for the railway are one of the critical parts of the signaling system [1, 2]. Several methods have been innovated for this purpose in which track circuits play a vital role and have an assertive part [3, 4]. Track circuits are commonly electrical circuits capable of train existence detection in a limited section of the rail called a track section. This detection leads to proper control commands and therefore, absolute safety for transportation [1-3]. All types of track circuits generally include an electric source, an electric active load, and occasionally a switch. Since the rail is made of steel, it is utilized as the conductor in almost all types of the track circuit. According to the electric source used in track circuits, they are classified into four majors [5]:

1. DC track circuits
2. AC track circuits
3. Impulse track circuits
4. Audio frequency track circuits

The system functioning in all types is found on short circuit effect caused by wheel and axel between two rails [6]. Figure 1 shows the structure of a simple DC track circuit.

The short circuit after the train's entrance changes the state of a control relay. This sign can be an indicator of the train's presence. In Figure 1(A), the track section is empty and the relay is energized while after the first axel enters the track section, it plays as a short circuit and consequently, the relay would be de-energized.

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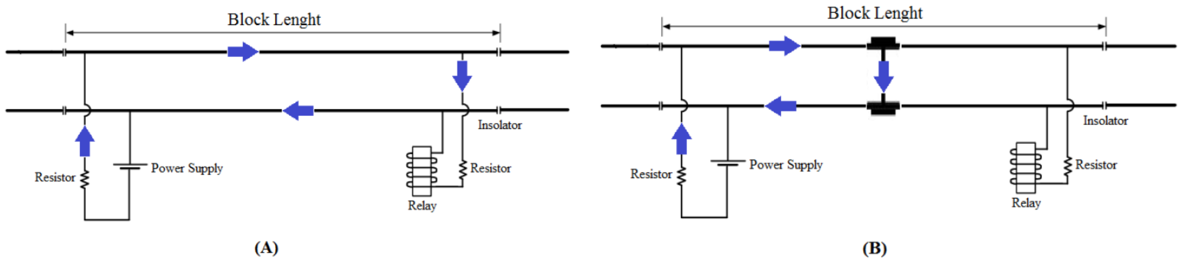

Figure 1. An example of a DC track circuit. (A) the train did not occupy the block and the relay is activated. (B) the train entered the block, causing a short circuit, and deactivated the relay.

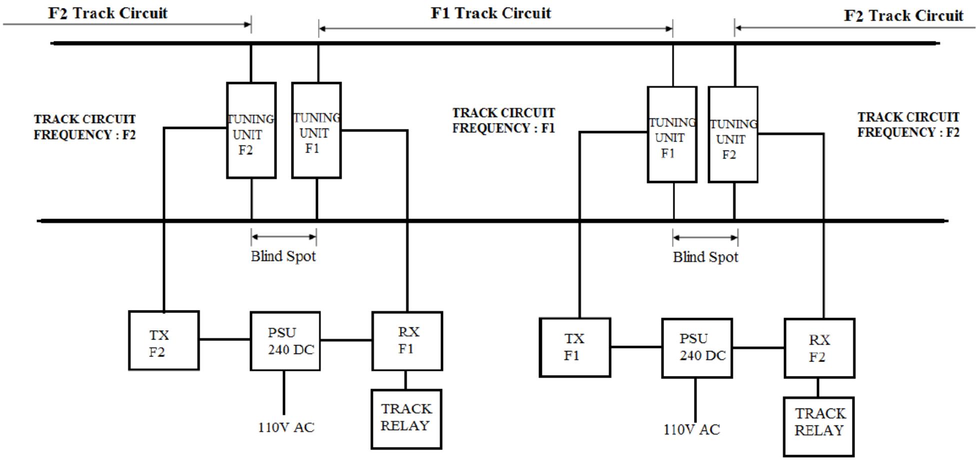

Figure 2. The topology of the AF track circuit.

The same logic is adopted for AC track circuits while the DC source is substituted by an AC source and a Vane relay takes the place of the normal relay to function with AC [7]. Despite of simplicity of DC and AC track circuits several factors such as the ballast resistance effect and its instability, eddy current, the difficulty of drainage operation, etc. put palpable restrictions on their usages. These limits of AC and DC track circuits can be solved by their substitution as Impulse and Audio Frequency [8] track circuits. Meanwhile, due to the need for track isolation for Impulse Track Circuits, AF (audio frequency) track circuits are more convenient for practical matters [8, 9]. AF track circuits regarded as non-junction track circuits [8, 10] are designed for usage in high interference conditions and are capable of functioning for all DC, AC, and non-electric railways. In this system, each circuit is allocated for a single track section working with an AC voltage and a specific frequency. By utilizing different frequencies and their periodic placement, each AF track circuit can be divided from the others. In the receiver, the recognition task is done according to 3 conditions. These 3 conditions are as below [11]:

1. Frequency matching between the carrier signal and the frequency.
2. Satisfying a certain energy level for the received signal
3. Code matching between the modulating signal and the defined code of the track

Any breach of mentioned conditions will lead to an occupied track signal. The AF track circuit block diagram is illustrated in Figure 2.

According to the structure shown in Figure 2, the presence of a wheel and axel on the rail will cut the connection between the transmitter and receiver.

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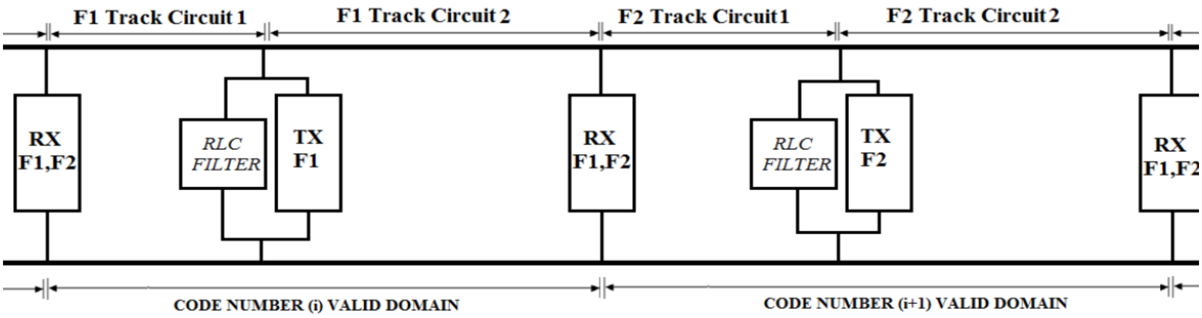

Figure 3. The amended AF track circuit topology.

Therefore, the track would be assumed as occupied. Moreover, the track code and energy level check will guarantee the fail-safety of the system.

Alongside all the advantages of AF track circuits, the high implementation costs put restrictions on their usage since a couple of transmitters, and receivers for each track, are needed. Also, several blind spots exist in the system due to the topology presented in Figure 2. Blind spots are parts of the rail that, if any axel enters that zone, would be unrecognizable for the AF track circuit [11]. In this paper, two different modifications are purposed for the first time in which the mentioned problems of AF track circuits are considered and solved. Initially, a new topology is proposed by amending the structure of Figure 2. In the proposed approach, the number of receivers and transmitters is half of the previous topologies, and the problem of blind spots is solved. Then the second method is introduced in which the majority of the receivers from the rail side would be omitted and instead, a limited number of receivers on the wayside would be substituted. The rest of this paper is organized as below:

In sections 2 and 3, the amended topology and PAF track circuits are proposed, respectively. Section 4 represents the emulation and circuit analysis. The conclusion and further suggestions are considered in section 5.

2. AF Track Circuit with Amended Topology

According to Figure 2, due to the placement of receivers and the transmitters, blind spots are made. Also, it can be perceived that a couple of transmitter and receiver is required for each track section. Figure 3 shows our amended topology.

As shown in Figure 3, in this topology, each transmitter or receiver is common for both its siding tracks. It must be noted that the receiver is ameliorated to receive both its siding frequencies. This can be provided by an RLC filter. As the wheel and axel enter each track section, the connection between the pertinent receiver and its transmitter is cut. Therefore, the receiver detects the train's existence based on the absence of each of its two siding frequencies. For more safety impedance bounds are used to preserve receiving a signal from distant transmitters. Plus, the unique communication code between transmitter and receiver for each track section and the act of code matching between them guarantees system failure safety.

According to Figure 3, each transmitter and receiver are used for two track circuits mutually. This will end up in the reduction of the number of devices used for implementation, and therefore, the cost would be enormously reduced. Furthermore, the blind spots caused by the distance between two neighboring transmitters and receivers from separated track sections are removed in this topology.

3. Positioning AF (PAF) Track Circuit

The proposed method is described in this section. This approach is named the positioning audio frequency (PAF) track circuit since it has the capability of estimating the train's position on the occupied track. In the PAF track circuit, by using transmitters in audio frequencies and a proper receiver block wayside, all the receivers

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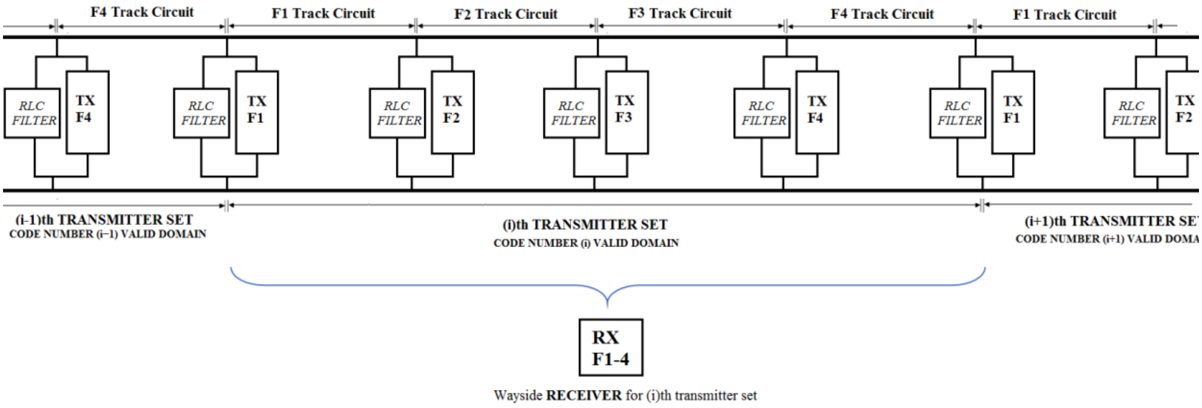

Figure 4. The topology of the PAF track circuit.

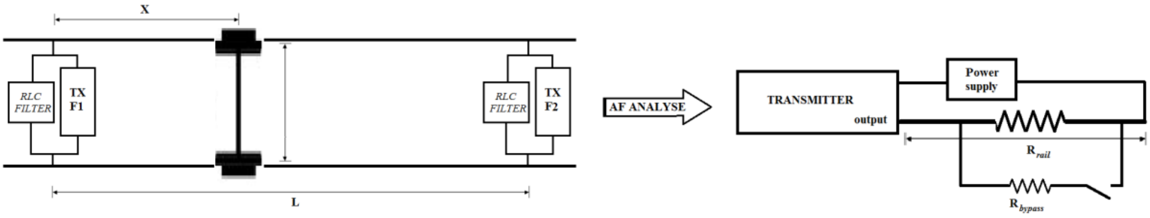

Figure 5. Using rail resistance to connect transmitters to the power supply. A parallel resistor can be implanted into R_{rail} to reduce energy loss but the caballing must avoid R_{bypass} to connect the circuit in the absence of R_{rail}.

from the rail, the side is omitted. Figure 4 illustrates the block diagram of the proposed method for rail lines.

The AF frequency transmitter used in this method utilizes rail steel as the input resistance in the circuit. The high length of tracks and low electric resistance of the rail enable this option. Transmitter circuits are designed in such a way that only in case of the wheelset existence (short circuit), does the transmitter connect with the power supply. Track length (resistance) is limited by impedance bounds. According to Figure 4, the transmitter Ti works with a carrier with fi as frequency. Four different frequencies are applied to the transmitter set (each transmitter has a unique frequency) and then the transmitter set is repeated periodically to extend the whole route. A decision-making block containing 4 receivers (for each of the frequencies) monitors the train position on the wayside. This data can be used in ATC (automatic train control) and also can be sent to CTC (centralized traffic control). Figure 5 shows the transmitter logic.

In Figure 5, x represents the distance between the transmitter and the closest axel of the train. When the first train's axel enters the track section starting from transmitter joints, the variable x begins in value from 0 and grows as the train passes through the track section until x reaches its maximum size which is the track section length. Since the transmitter is designed to work with a certain resistance, a bypass resistor is added in parallel with rail resistance to prevent any distractions. However, in the transmitter circuit, the rail resistance is used to bias the oscillator. This bias affects the output amplitude as the value of x changes over the travel.

In other words, the receiver in the wayside will sense a drop in the amplitude of the received signal of the specific frequency as the train moves on. This drop gets more prominent as the train keeps moving because the effective resistance is increasing as well. Based on this fact it is possible not only to detect an occupied track section but also to estimate the train position along in track. As the last axle of the train exits the track, the transmitter circuit gets disconnected from the power supply, and the next transmitter gets activated. This sequence plays a key role in train detection.

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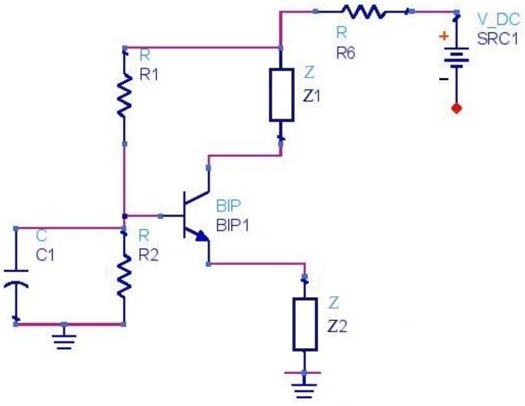

Figure 6. Bias configuration for Colpitts oscillator using common base structure.

A unique code is allocated to each set of transmitters to distinguish each set from another. Four different frequencies are used in each set to increase system safety and reliability. This number can be increased or decreased according to the transmitters’ quality, and it is better to reach a fixed number through practical experiments.

2.1. Transmitter Circuit

Unlike other frequency track circuits, in the proposed circuit, bias resistors R1 and R2 are defined in terms of rail track resistance in the Colpitts oscillator structure. In general, a transistor circuit is shown as a common base in Figure 6.

In most cases, the value of rail track resistance in short distances is usually assumed to be negligible, although this resistance has a significant value in longer routes. For example, in [12-17], the value of resistance and impedance of the rail track is defined as follows:

$$R_{rail} = \frac{\rho \times \ell}{A} \qquad (1)$$

Where, ρ is a constant coefficient of steel, ℓ is the length (m), and A is the cross-section (m^2). Studies on rail track resistance in audio frequency suggest the value of 0.5-90 micro ohm-cm [15, 18, 19]. The maximum length of track sections is set to 900 m to restrict rail resistance to 8 ohms. This restriction is to avoid transistors to remain in working mode and voltage loss does not extend unnecessarily.

In a Colpitts oscillator circuit, the collector (output) voltage is defined as follows [20].

$$v_c = 2.I_c.R_L.\sqrt{\frac{c_2}{c_1 + c_2}} \qquad (2)$$

where I_c is the collector's current, R_L is the collector’s load and c_1 and c_2 are the tuning capacitors. I_c current is proportional to the base voltage [21]. Therefore, if there are changes in the ratio of resistances R_1 and R_2, these changes will also appear in the amplitude of the output waveform of the oscillator. Using such an idea, we added the resistance of a part of the rail that the train has traveled to resistances R_1 and R_2 so that the amplitude of the output waveform is indirectly a function of the route traveled. In this way, we define the bias resistors as below (figure 7) which is in parallel with the first and second resistors.

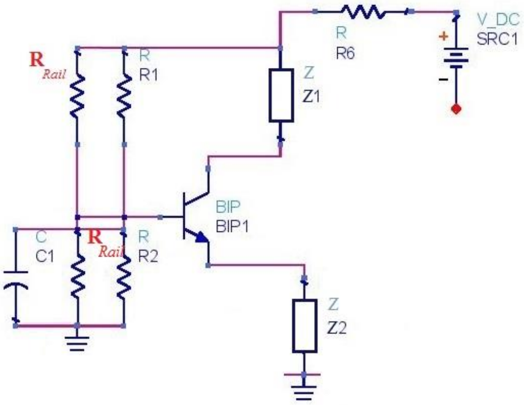

Figure 7. Bias configuration using rail track resistance.

Using equation 1, the output voltage and amplitude can be assumed as follows.

$$v_c \propto \frac{R_1 R_2 R_{Rail} + R_1 R^2_{Rail}}{2R_1 R_2 R_{Rail} + R_1 R^2_{Rail} + R_2 R^2_{Rail}} \qquad (3)$$

Using such structure for the bias, the distance traveled by a train on a specific track affects the amplitude of the signal, and by measuring the amplitude in the receiver, not only can the presence of the train be detected in the tracker, but its position can be determined with an

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acceptable approximation. It is necessary to mention that changes in resistors R_1 and R_2 do not affect the output frequency, but their values should be selected in such a way that the transistor is activated in its working mode and the collector current is higher than a certain minimum. For this purpose, we modify the rail resistance as presented in Figure 8, which uses alpha and beta resistors to meet the base current settings and transistor activation requirements.

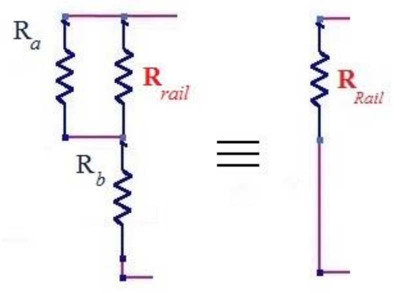

Figure 8. Tuning rail resistance using R_a and R_b.

The audio frequency transmitter used in the proposed method is described in this section. The transmitter circuit is presented in Figure 9.

The transmitter circuit illustrated in figure 9, includes 3 major blocks. Block A is an oscillator to generate the carrier signal by the Colpitts structure. With tuning capacitors, C_1, C_2, and C_3 the f as the transmitter's carrier frequency can be reached. AM modulation is chosen due to its simplicity as shown in block B.

The track set code as the modulating signal is injected into the base of the Q1 transistor by IN entrance. This base current is multiplied by β (the transistor parameter) and $\beta + 1$ making the collector and emitter currents respectively. Because the lower section of block B works as a current source for the mirror transistors, the collectors' current of the Q_3 transistor is the summation of the carrier's frequency harmonics multiplied by modulating code. An RLC filter is applied to elicit the main harmonic to be transmitted to the buffer section in block C. Current supplement and impedance matching are done by tuning the values of L_1, and R_1. The desired frequencies of f_1, f_2, f_3, and f_4 can be achieved by tuning tank capacitors and inductors using the equation $f = 1/2\pi\sqrt{L\frac{C_1C_2}{C_1+C_2}}$ explained in [20, 22]. Using such an equation, by setting c_2, c_3, and c_7 to 1 and c_4 to 2 mF (setting tank capacitors to 1 mF), for L1 with 2, 3, 5, and 7 mH, four oscillation frequencies 160 Hz, 130 Hz, 100 Hz, and 85 Hz can be achieved as f_1, f_2, f_3, and f_4.

3.2. Receiver Circuit

The receiver type must be in accord with the modulation type chosen for the transmitter. For AM modulation, a tuned audio frequency receiver with an RF amplifier is an acceptable option. Figure 10 represents this receiver circuit.

Block A in Figure 10 performs as an amplifier meanwhile, the RLC circuit in the collector section of the Q1 transistor filters all neighboring frequencies but the desired f.

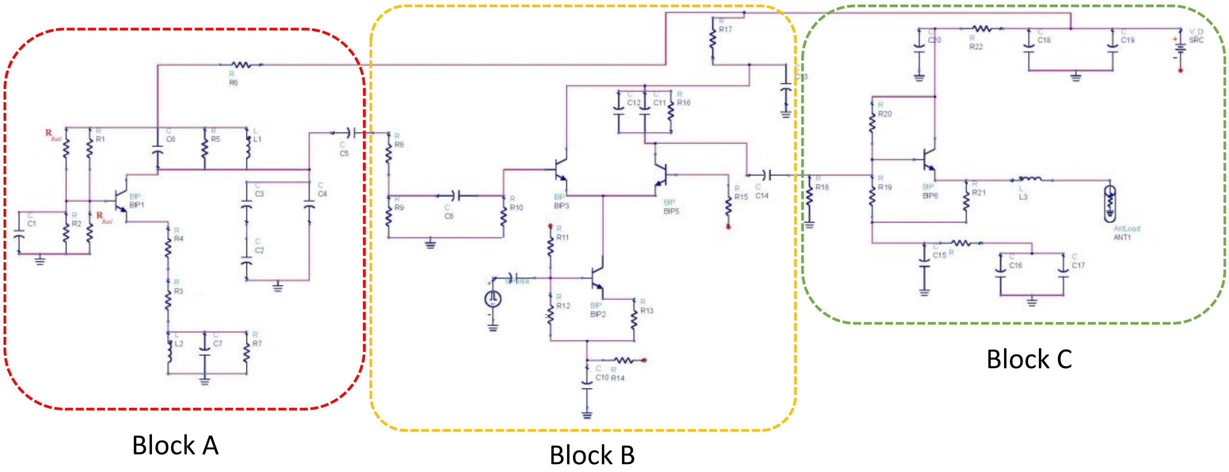

Figure 9. The transmitter circuit for the PAF track circuit.

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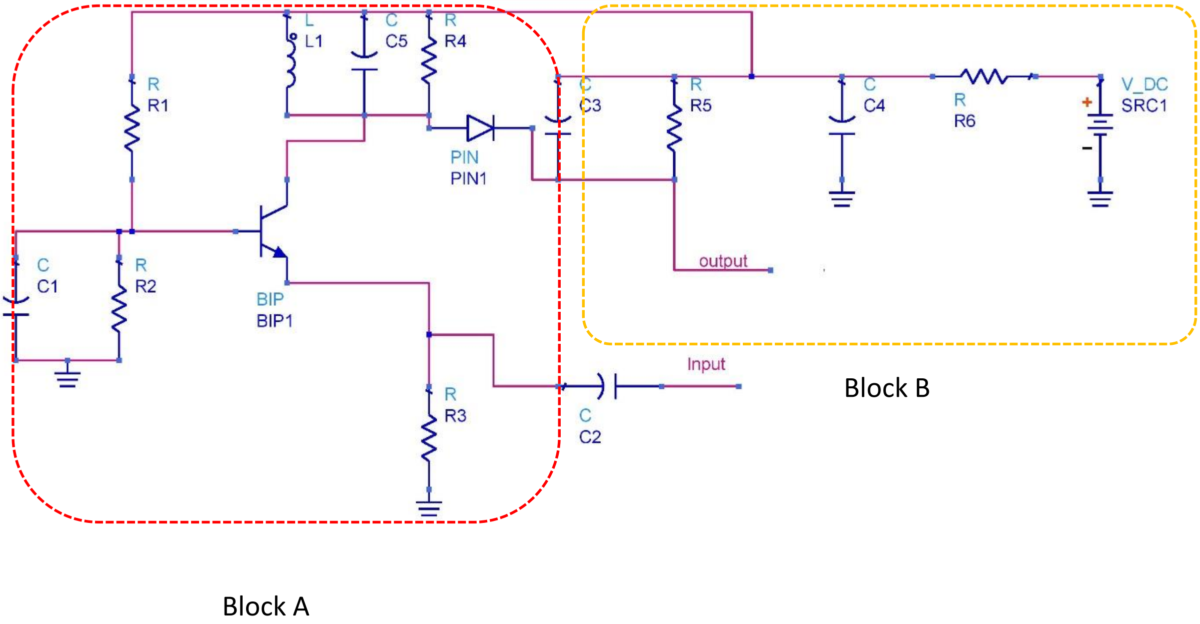

Figure 10. The receiver circuit.

Block B is an envelope detector. The final output is conducted to a decision-making block for code matching and amplitude level check to detect the condition of the track section based on the explanation of the previous section. All the elements of both transmitter and receiver circuits can be shifted in values based on the desired frequencies for f1, f2, f3, and f4. This property extends the system's flexibility in comparison with AF track circuits.

3.3. Interaction with ATP System

The automatic train protection (ATP) system is a system that is obliged to stop the train independently of manual or automatic driving decisions, taking into account safety issues to prevent possible accidents and violations of the speed limit [23, 24]. By using the proposed PAF track circuit system, we can equip the ATP system with new features. By adding a wayside receiver unit to the ATP equipment inside the train, this system can estimate the speed changes by continuously monitoring the input signal gain in the receiver and it can stop the train if necessary. At any moment, the train is required to comply with a speed profile and a maximum amount proportional to the acceleration, which is already calculated or calculated online [24]. Using the proposed track circuit system, the ATP system can measure the rate of signal gain changes and compare it with its reference and make control decisions.

In addition, in the proposed circuit design, each transmitter is connected to the power source if the train creates a connection between two rails. As a result, only one transmitter related to the occupied track is active at the moment. In this sense, if another train is moving near the train and the adjacent tracks are occupied, the ATP receiver system in both trains will also receive the signal of another transmitter. (Each receiver is capable of receiving four track frequencies), and the ATP system can stop the train before entering the occupied track. As a result, the proposed circuit system can be of great help to the ATP system concerns. The behavioral block diagram of the ATP system and its interaction with the proposed AF track circuit system is shown in Figure 11.

4. Simulation and Results

For the simulations, we applied rail characteristics presented in [25-27]. For a set of frequencies as f1, f2, f3, and f4 (160 Hz, 130 Hz, 100 Hz, and 85 Hz), the elements of the transmitter and receiver are calculated and all the values are illustrated in Figure 12. R_a and R_b (in Figure 8) are set to the maximum of rail resistance (8 ohm) to mitigate power loss. Mind that there is no theoretical way to prove so.

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Therefore, the stability of the purpose circuits (with oscillators) is assured by comparing the outputs with other proven oscillators, and frequency stability is Checked and compared with a solid frequently in the long term in ADS software.

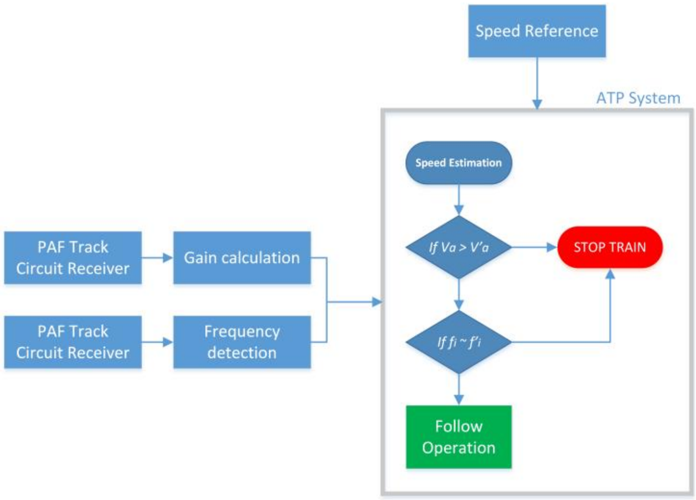

Figure 11. ATP interaction with track circuit.

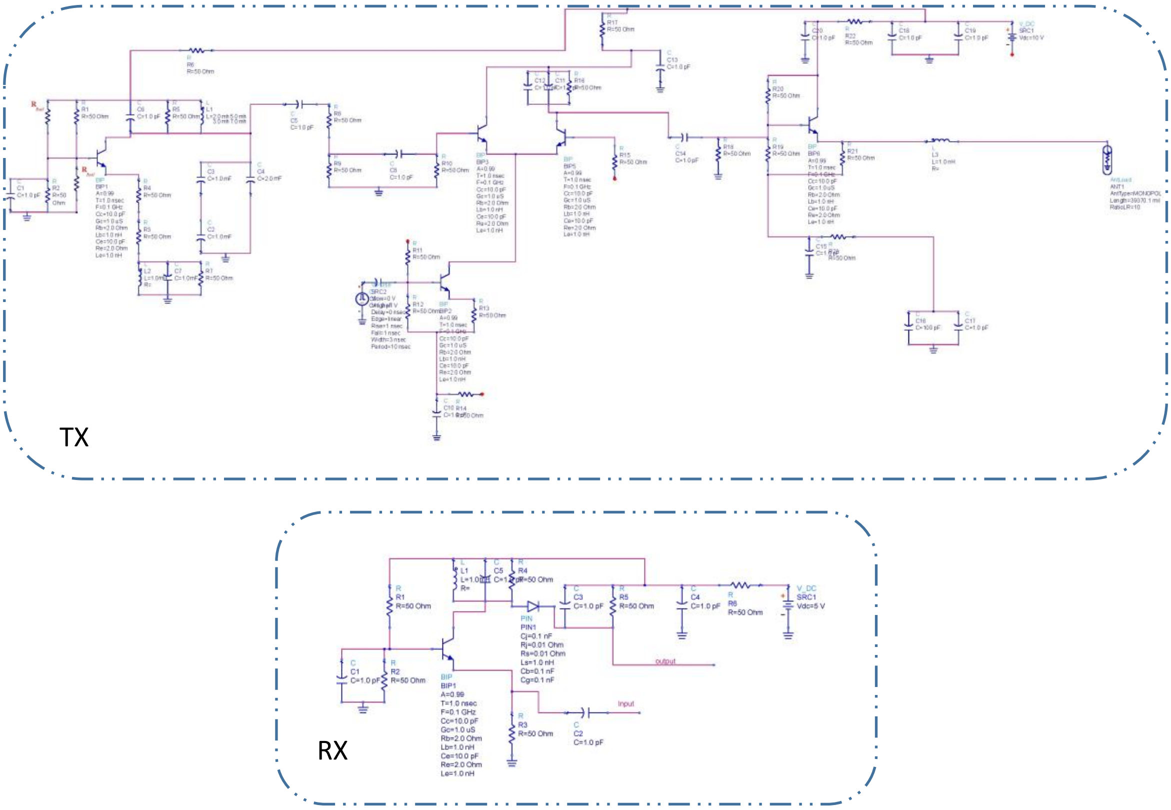

Figure 12. Parameters values for transmitter and receiver in PAF track circuit.

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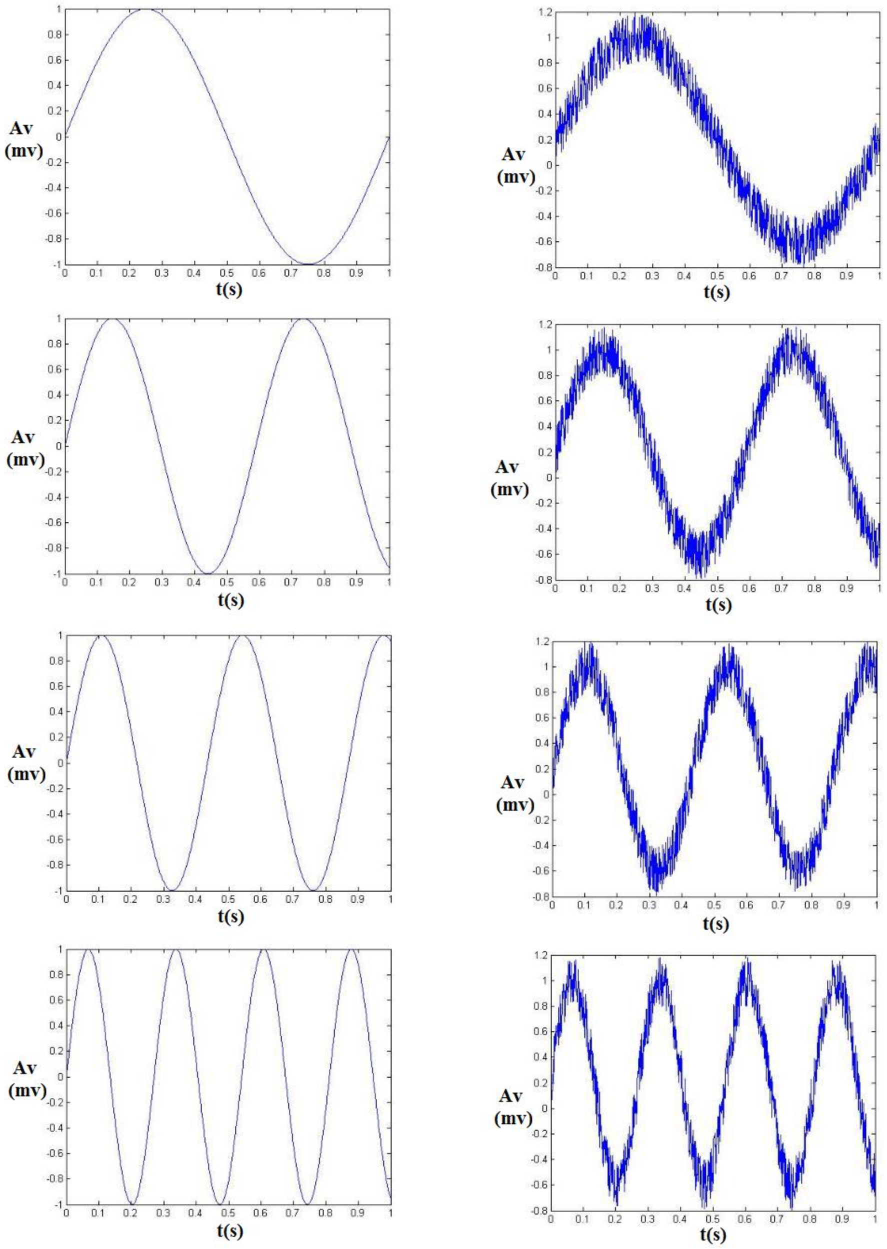

Figure 13. The transmitted and received signals for four sequences of the PAF track circuit.

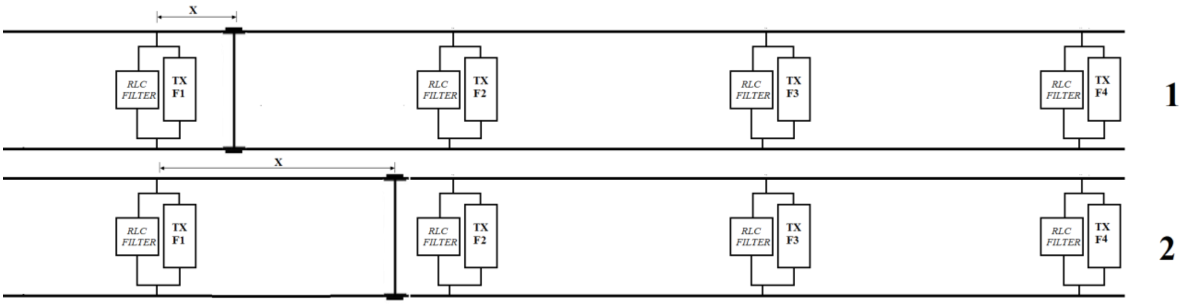

Figure 14. Test scenarios for the train's movement. In Scenario 1 the train axel just entered the track and in Scenario 2, the last axel is leaving the track.

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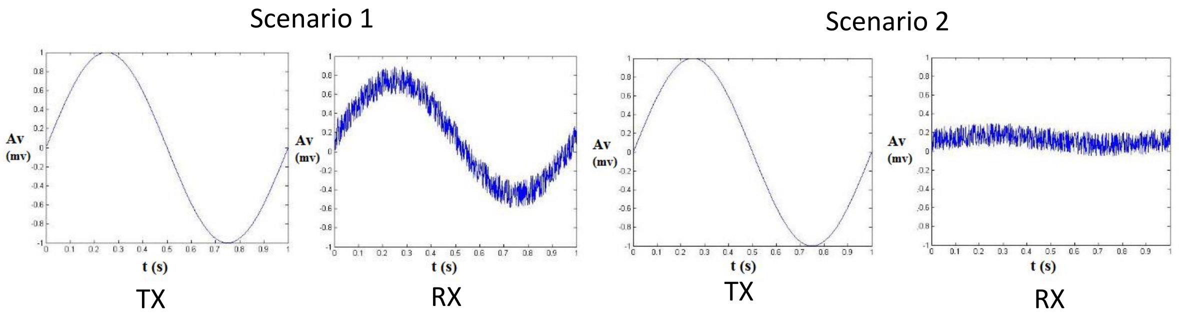

Figure 15. Test results for scenarios 1 and 2. The y axis is the voltage (mv) and the x axis is the time (s).

Vibration noise and distractions presented in [28-30] are added to simulate the practical conditions. Figure 13 represents the transmitted and received signals for four sequence frequencies. Due to the lack of any disruption, the receiver output follows the transmitter perfectly with an acceptable voltage gain Av≈1.

For further clarification, consider the following scenarios in Figure 14. In Figure 14, x is the distance between the transmitter and the closest axel within the occupied track section. Simulation results for scenarios 1 and 2 are shown in Figure 15.

As discussed earlier in sections 2 and 3, in scenario 1; since the rail resistance (x length) is much smaller than its maximum size, the received signal has a high voltage gain (A_{v1} = 0.9). On the other hand, in scenario 2, while the x length has an assertive growth, this gain decreased from 0.9 to 0.1. Based on more detailed simulations presented in Figure 16, the voltage gains (A_v) have a linear relation with x. Figure 17 shows this concern.

It can be understood from Figure 16 that A_{vi} is the corresponding receiver gain to Xi. It can be seen that as xi decreases, the gain follows this growth. Figure 17 considers A_{vi} in y axel corresponding to Xi for much palpable consideration.

Based on the results, it can be seen that as the train moves on a track section, a drop in voltage gain corresponding to the track frequency transmitter occurs. The combination of this drop and modulation code received from the other three signals can be used to recognize the occupied track and train approximate positioning. Note that a similar code is allotted to each set of transmitters.

This redundancy will help the code detection and safety of the whole system. The sequence of train movement can be used as a check for ATC (automatic train control) for monitoring system failure. Moreover, if the train breaks from any point, the gain of the corresponding track frequency will stop increasing and remains constant or even starts decreasing. This can be a sign recognizing the integrity failure.

The improvement of the purpose method comfort to the current versions of track circuits is its ability to allocate the train to the track without the use of a global positioning system for any advanced technology. Moreover, the implementation costs or lower due to the fewer number of components in a single track. For comparison purposes, the summary of the components is presented in Table 1.

Table 1. Elements summery.

Number of Transmitters (TX)	**Number of Receivers (RX)**	**Transistors in TX**	**Transistors in RX**	**Total electric components in TX**	**Total electric components in RX**	**Positioning ability on each track**
4	1	5	1	52	15	✓

6. Conclusions

This work studied frequency track circuits as one of the major types of track circuits. To overcome the fundamental problems of AF track circuits: 1-implementation costs and 2-blind spots, two different modifications were proposed. In the first step, the receiver and transmitter topology was amended to use each receiver or transmitter mutually for two track circuits.

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Therefore, the number of receivers and transmitters becomes half, and blind spots that existed due to distance between neighboring sections are eliminated. In the second proposal, by utilizing audio frequency receivers and transmitters discussed in section 3, all the on-rail receivers were substituted by a wayside receiver.

This elimination leads to a huge cost reduction. It was claimed that by using rail as the bias impedance for the transmitter, the train movement changes the resistance and the effective length of the track, and therefore the gain of received signal varies according to the position of the train on the rail. This fact was proved in simulation and can be used to detect track occupation and the train position in the track with track circuits for the first time. For further studies, optimization of the number of frequencies the track sets based on practical implementation, and usage of different oscillators and RF amplifiers and their effect on RF track circuits are suggested.

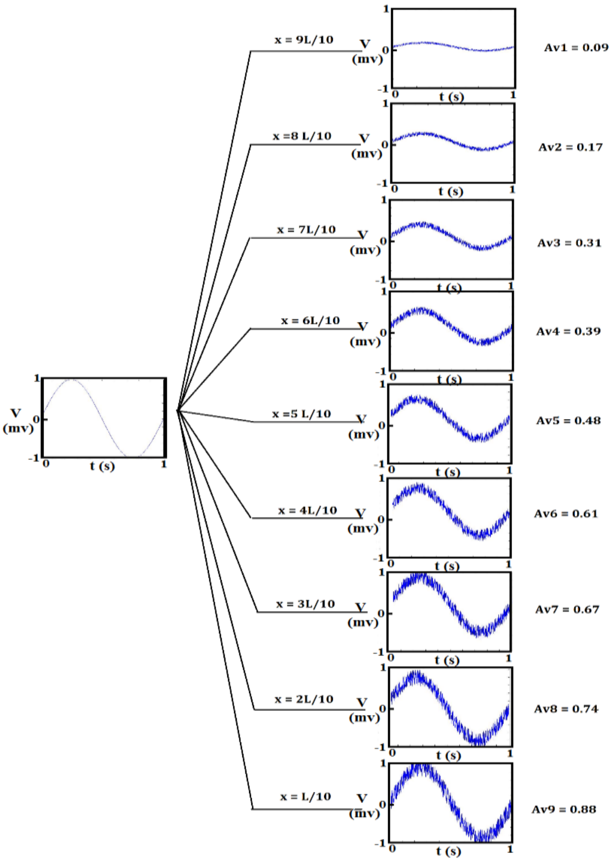

Figure 16. The received signal in different train positioning.

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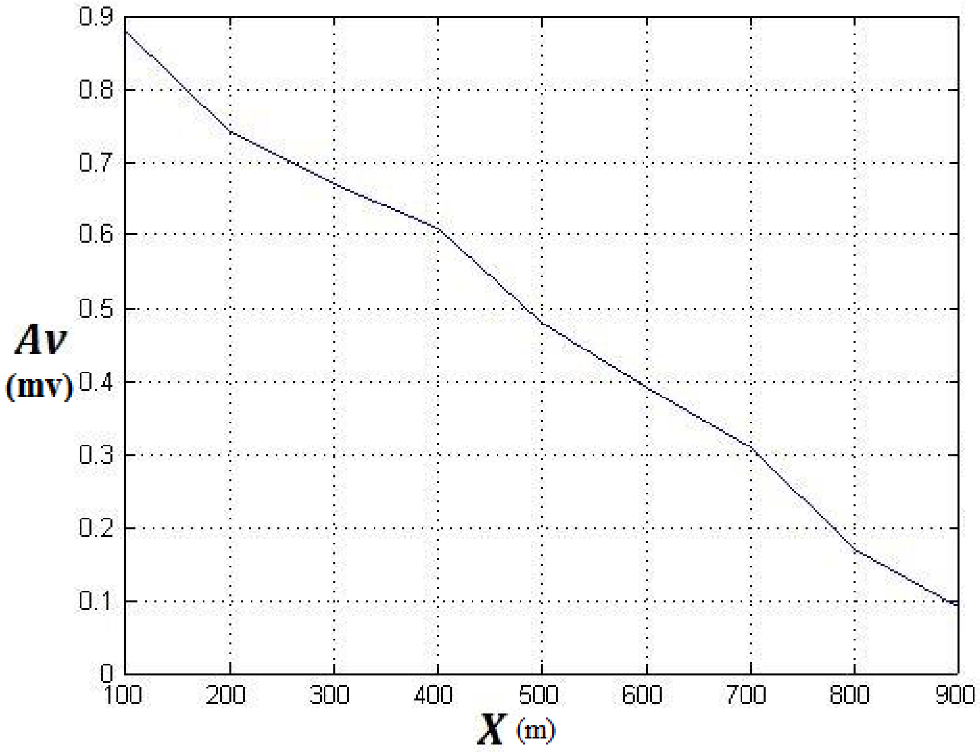

Figure 17. The linear relation between train position and signal gain.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

List of abbreviations

The list of acronyms and abbreviations is as follows.

ATP	Automatic train protection
ATC	Automatic train control
AC	Alternating current
AF	Audio frequency
DC	Direct current
PAF	Positioning audio frequency
CTC	Centralized traffic control
IN	Entrance/input
RF	Radio frequency
AM	Amplitude modulation

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