

Method and apparatus for detecting railway system defects

Field of the invention

5 The present invention relates to methods and apparatus for detecting faults in railway systems, such as defects in rails, and particularly to a system which is able to detect early stage rail defects in "real time" (that is, when the lines are in use for standard rail traffic, rather than during a separate maintenance operation).

Background of the invention

15 The passenger safety and service reliability have always been a top concern of the railway operators worldwide. Signaling errors and rail defects are two major causes [1-2] for service breakdowns and accidents, such as derailments [3]. Whereas railway control signals can be easily monitored for any abnormality, the mechanical defects of the rails are more difficult to detect in real time, and are usually detected during scheduled maintenance.

20 In addition to the two "running rails" on which a conventional train runs, it is very common to supply electric power to the electric traction system(s) of a train via a rail carrying a high voltage (which may be positive or negative). Such a power supply rail is referred to here as a "third rail" (though the term is to be understood as encompassing also the high voltage rail of railway system, such as a monorail system, in which the number of running rails is not equal to two). The third rail is maintained at a high DC voltage (usually 750V or higher). Fig. 1 is a photograph of a portion of a conventional electric train, and as illustrated, the train is provided with a collector shoe (the element within the ellipse 1) which has an upper surface 2 which glides along the bottom of the third rail, to receive the DC voltage.

30 Since the third rail transmits electric power to the electric traction system, its condition has a direct impact on the train service reliability and passenger safety.

The oldest method of detecting rail defects was visual inspection. Unfortunately, visual inspection can only detect external defects that are clearly visible and is unable to detect internal defects of the rail, such as transverse fissures, which are internal separations of the steel within the rail head. Such defects are known to have led to serious accidents, so more sophisticated defect detection techniques have been developed.

Current rail inspection methods adopt either ultrasonic or eddy current techniques, which mainly focus on detecting defects in the two running rails instead of the condition of the third rail. The ultrasonic technique requires a dedicated rail inspection vehicle. Ultrasonic probes and transducers are attached to the vehicle for checking the condition of the railway track. Due to the response time of an ultrasonic guided wave, typical inspection speeds of commercially available ultrasonic inspection vehicles are less than 60 km/h [4]. Due to this speed limit constraint, ultrasonic inspection equipment cannot be installed on in-service trains. Therefore the rail inspection can only be carried out during the off-service hours.

The eddy current technique uses an induced electromagnetic field to generate an eddy current on the surface of the rails, as illustrated in Fig. 2, which is taken from [5]. It cannot detect surface defects which are parallel to the induced eddy current and hence, it is not as popular as the ultrasonic technique. In most cases, the eddy current inspection equipment will only be assembled on the ultrasonic inspection vehicle when higher inspection accuracy is needed. To the best of our knowledge, all the existing inspection techniques only inspect the running railway track but not the railway electrification system consisting of a third rail, collector shoes and the electric traction system of the train.

With increasing rail traffic frequency and extending operating hours, the existing rail inspection techniques are apparently unsatisfactory. A more efficient way of detecting early-stage of rail defects is needed.

5 Summary of the invention

The present invention aims to provide a new and useful method and apparatus for detecting defects in railway systems.

10 In general terms, the invention proposes that an alternating electrical signal is induced in a component of a rail vehicle (typically the electric locomotive) which is electrically connected to a rail. The signal is inductively detected, and a signal processing operation is performed to identify defects based on the detected signal.

15 Under normal circumstances, the detected signal is of a specific level. If there is any abnormality, for example a poor electrical contact due to partially damaged rail (higher impedance) or a partial-short of motor (lower impedance), the impedance associated with the rail changes, which will be reflected by the
20 detected signal having a lower or higher amplitude than its normal level.

A more specific expression of the invention is a method of detecting a fault in an electric railway system including a running rail, a power supply rail, and a rail vehicle moving along the running rail and receiving electric power from the power
25 supply rail, the method including:

 generating a first alternating electric signal using an alternating signal generation unit mounted in the rail vehicle,

 using a first inductive coupling unit mounted in the rail vehicle to inductively transmit the first alternating electric signal to a component of the rail
30 vehicle which is electrically connected to a said rail, to create a second alternating electric signal in said component;

using a second inductive coupling unit mounted in the rail vehicle to inductively generate a third alternating electric signal from the second alternating electric signal; and

5 performing a signal processing operation on the third alternating electric signal, and thereby detecting the fault.

The invention can also be expressed in terms of a fault detection apparatus for location on the rail vehicle, and configured to carry out the method, by generating and processing the alternating electric signals.

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The proposed method is not subject to the speed constraint of an ultrasonic system, and this makes possible real-time inspection of the rail without interrupting normal train services. Hence, any emergence of rail defects can be detected early before the next maintenance schedule, and without interrupting

15 the normal operation of train services.

Alternatively or additionally, the method may be used by a specialized inspection vehicle which travels at lower speed than conventional trains, and is thereby able to detect very fine cracks.

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In either case, the method can greatly reduce the rail's maintenance cost, avoid major train breakdowns and enhance the train service reliability. If the proposed method is implemented, the train operators can reduce the maintenance frequency, saving significant manpower and expenses on maintenance. Also,

25 quick response to the early-stage damage of the rail avoids major train breakdowns, which not only tarnish the images of the train operators, and saves unproductive manpower of passengers who are affected by the breakdowns.

The alternating electric signal preferably includes at least one component with a frequency in the radio frequency (RF) range. That is, at least about 3 kHz and at

30 most about 300 GHz. At least one component of the alternating electric signal

(and more preferably, substantially all components of the signal) preferably has a frequency of at least 300 kHz, and preferably has a frequency of no more than 100 MHz. Frequencies below 300 KHz overlap with the switching harmonics of the electrical drive. For frequencies above 100 MHz the RF impedance may be very large so that it is harder to detect the impedance variation due to rail defects. The method may be implemented by an apparatus which includes no moving parts and therefore is highly reliable.

The component is typically electrically connected directly to the collector shoe (that is, without intervening circuitry which substantially alters the voltage) which collects electric power from the power supply rail (third rail). The proposed method can be implemented when the third rail is connected to high-voltage power supply (usually 750 V DC or higher). Generating the second and third alternating electrical signals inductively ensures that the circuitry which generates the first alternating electrical signal, and the circuitry which processes the third alternating electrical signal, have no direct electrical connection to the high voltage power (750 V or even higher) system of the third rail. This protects the circuitry from damage (if the protection was alternatively provided with electrical insulation, that might be subject to insulation breakdown). It also ensures electrical safety for the personnel who handle the circuitry.

Unlike the existing rail inspection techniques which can only inspect a rail's defects, the proposed method may in addition also detect any abnormal performance of the train's locomotive since it is electrically connected to the third rail as part of the circuit loop being inspected. Thus, the method may detect faults in a collector shoe or in the electrical drive system of the train.

A given train typically has multiple collector shoes (e.g. four per compartment). Optionally, the first alternating electric signal can be used to generate inductively second alternating electric signals in respective components connected to each of multiple shoes. The second alternating electric signals are used to generate

inductively respective third alternating electric signals, and each of these can be subject to the signal processing operation (e.g. in turn) so that faults in each of the shoes can be detected.

- 5 The proposed invention not only detects the defects of the electrification system in real-time but also has the ability to differentiate various defects, as well as to locate the specific section of the damaged third rail.

10 The circuit monitors the abnormality of the entire electrification system of the train, including collector shoes, electric motor and the third rail, in real-time when the train moves along the railway track. Hence, the electrification system at specific section of the railway track will be checked every few minutes by a passing train with the installed detection module. This will allow early-stage damages of collector shoes, third rail and electric motor be detected before the next
15 scheduled inspection.

20 The proposed fault detection apparatus can be made modular and easily installed in the train. Therefore, it eliminates the need for a separate inspection vehicle. The proposed inspection circuit requires little physical space and most components are easily available in the market, which makes it highly cost effective as compared with the ultrasonic inspection.

25 With some modification, the proposed method can also detect the exact location of the damaged part without checking the entire section of the rail, which can be easily a few km in length. This is done by arranging for the fault detection apparatus to include or be coupled to a location detection unit. The location detection unit may be a Global Positioning System (GPS) unit and/or the train's tachometer. In this way, embodiments of the proposed invention can locate the any defects on the third rail, making maintenance and repair of the third rail
30 highly efficient.

Brief description of the figures

Embodiments of the invention will now be described for the sake of example only with reference to the following figures in which:

Fig. 1 illustrates a conventional system for receiving a voltage from the third rail of a railway system;

Fig. 2 illustrates a known device for detecting defects in a rail by the generation of eddy currents;

Fig. 3 illustrates a first embodiment of the invention;

Fig. 4 is composed of Fig. 4(a) and Fig. 4(b) which are respectively (a) a block diagram and (b) a schematic circuit of a detection instrument of the embodiment of Fig. 3;

Fig. 5 illustrates a second embodiment of the invention;

Fig. 6 illustrates transmission of data from an apparatus which is an embodiment of the invention to a train control centre;

Fig. 7 is an illustration of one form of the second embodiment of the invention; and

Fig. 8 shows experimental results from a prototype of the invention.

Detailed description of the embodiments

A first embodiment of the invention is illustrated in Fig. 3. The embodiment is explained in terms of three major circuit modules. The first is the circuit under inspection module ("signal injecting module"), which is the system including the train and the rails, including in particular the third rail. The second circuit module is a signal injecting module, comprising an alternating signal generation unit ("signal source") for generating a first alternating electric signal, and coupled to a first inductive coupling unit ("RF signal injecting inductive-coupling probe") for generating a second alternating electric signal in a component electrically connected to the third rail. The third circuit module is the signal receiving module, comprising a second inductive coupling unit ("RF signal receiving inductive-

coupling probe”) for inductively generating a third alternating electric signal, and a signal processing unit (“detection instrument”).

5 Note that in this embodiment, the component in which the second alternating electric signal is generated is electrically connected to both the third rail and a portion of one of the running rails. A capacitor is provided in the signal injecting module to prevent a direct current short circuit.

10 The block diagram and schematic circuit of the detecting instrument are shown in Figs. 4(a) and 4(b), respectively. The detecting instrument includes (i) an RF signal receiver including an inductive coupling coil, (ii) a rectifier for generating a DC signal V_{Rec} indicative of the amplitude of the third alternating electric signal, (iii) a comparator which compares V_{Rec} to two thresholds V_{ref1} and V_{ref2} to produce respective signals V_{out1} and V_{out2} , and (iv) a defect indicator which
15 generates a light signal when V_{out1} is above a threshold, and inverts V_{out2} and generates a light signal when the result is above a threshold.

A second embodiment of the invention is illustrated with reference to Fig. 5. A conventional train traction system is illustrated schematically. A third rail (positive
20 terminal) and a first one of the two running rails (negative terminal) are powered by a high voltage DC power supply (e.g. 750 V). The DC current is returned via an axle brush to the first of the running rails. The electric power drive of the train receives its power supply current from the third rail through one or more collector shoes (only one is illustrated) and the first running rail, which form a complete
25 circuit loop. The solid arrows in Fig. 5 show the direction of the DC supply current of the electric traction circuit.

To detect the defects of the electric traction (e.g. broken collector shoes or damaged third rail), a radio frequency (RF) signal is injected inductively to the
30 electric traction circuit and the injected signal level will be monitored inductively with a receiving circuit including an inspection circuit.

The RF signal is generated by an alternating signal generation unit ("RF signal source") in the form of a first alternating electric signal. The alternating signal generating unit is coupled to a first inductive coupling unit ("magnetic core to inject RF signal") for generating a second alternating electric signal in a component electrically connected to the collector shoe, which in turn is connected to the third rail. The dashed arrows in Fig. 5 illustrate how the second alternating electric signal flows through a closed loop including the train's traction system. A capacitor connects the axle brush and the collector shoe, and provides a return path for the RF signal.

A second inductive coupling unit ("magnetic core to receive RF signal") inductively generates a third alternating electric signal, which is supplied to a signal processing unit ("inspection circuit"). The inspection circuit includes a defect detection circuit unit, a defect indicator unit and a GPS tracker module.

Under normal circumstances, the electric power drive is connected to the third rail by a high quality electric connection, and the third alternating electric signal is of a specific level. However, if there is any abnormality, for example poor electric contact due to a partially damaged rail or damaged collector shoes (resulting in higher impedance) or a partial-short of the motor (resulting in lower impedance), the third alternating electric signal RF signal will vary from its normal level. Once the abnormality is detected, an alarm signal will be indicated and the GPS tracker module of the inspection circuit will also be activated. The GPS tracker module will notify the train control center as shown in Fig. 6, for example by a wireless transmitter of the inspection circuit.

In a variation of the above, the inspection circuit is still provided with a wireless transmitter, but instead of the GPS tracker module the inspection circuit receives an input from a tachometer of the train. This specific form of the embodiment of

Fig. 5 is illustrated in Fig. 7. The RF impedance of the components of the electrical drive system within the dotted line will vary only slightly during normal train operation. However, when there is a third rail defect (for example, a sagging third rail) or collector shoe defect (cracked or broken shoe), the electrical contact
5 to the third rail deteriorates and much higher impedance is expected, which results in a much lower received RF signal. The impedance variation can be a combination of inductance and capacitance.

In the second embodiment (as illustrated by Fig. 5) the inspection circuit can
10 differentiate whether the defect is related to the railway track or related to the train's electric traction system, and generates a corresponding alarm signal. If there is a defect on the running rails or on the third rail, the defect indicator will only generate an alarm signal when the train passes the defective section of the rail. Multiple trains of the type of Fig. 5 will generate respective alarm systems at
15 this defective section of the rail. The train control center is therefore able to alert the maintenance team to exact location of the defective rail for repair purposes.

Conversely, if the defect is caused by collector shoe(s) or the electric motor of the train, the alarm indicator will remain on. The train driver will then alert the
20 control center for the specific train to be sent for servicing.

The real-time monitoring of the condition of collector shoes is crucial, as they tend to wear out after some time. Usually, a few (one or two) detached collector shoes may not have any apparent impact on the train's performance. However, if
25 these detached collector shoes are not detected early, further damage to the remaining collector shoes will cause the train to come to a complete stall, resulting in major train service disruption.

Typically, a train compartment has four collector shoes: two on each side. Only the two which are on the same side of the compartment as the third rail are in use at any one time (for example, when the train is eastbound that will be the two collector shoes on one side of the train, and when the train is westbound that will be the two collector shoes on the other side of the train). In one form of the invention, an RF signal source and an RF signal monitoring circuit are provided for each compartment. Using the RF signal source, an RF signal may be inductively generated simultaneously in four components respectively connected to the four shoes, and the RF signal monitoring circuit would in this case receive four RF signals, and would process them in turn by multiplexing, so as to identify defects in any of the shoes. In other forms of the embodiment, the RF signal may be inductively generated simultaneously only in two components which are respectively connected to the two shoes on the same side of the compartment as the third rail, and the RF signal monitoring circuit would in this case receive two RF signals to process, e.g. with multiplexing, to identify defects in either of those two shoes.

Concept Validation

A preliminary prototype has been developed and tested on a model rail track and train. As explained above, the prototype has two major modules: the signal injecting module and the signal receiving module. The signal injecting module was implemented with inductive toroid coils and a capacitor in series. The RF signal was inductively coupled to the rail without direct electrical contact. The coil is in series with a capacitor so that the LC resonant frequency matches the RF signal frequency so that maximum signal power is inductively coupled to the rail.

The circuit under inspection consisted of a mini-rail and a motorized model train, and the circuit was as shown in Fig. 3. The motor of the model train received its

DC power through the rail, which is connected to a DC power supply. The mini-rail, model train and DC power supply emulate the real train operating environment. If any part of the rail is partially damaged or the motor malfunctions, an impedance change occurs and the monitored RF signal level varies accordingly. Experimental results using a 10MHz RF signal are given in Fig. 8. As shown, the prototype has the ability to detect impedance variation from 15 Ω to 2.4 k Ω , which has enough dynamic range to detect any abnormality of the train electric traction system.

10 The signal receiving module detected the injected RF signal from the circuit under inspection with an inductive coupling coil. The received RF signal was processed by a signal conditioning and processing circuit. The respective indicators were activated if the detected RF signal level was above or below pre-defined levels. The experimental results of the preliminary prototype demonstrated the aforesaid concept by indicating rail abnormalities in real-time.

Field trial

To ascertain that the induced RF signal does not affect the normal operation of an actual train, with the permission of Singapore Mass Rapid Transit (SMRT), a field trial was conducted on the form of the embodiment illustrated in Fig. 7 (which is presently our preferred implementation) using a moving train at the Bishan Depot Test Track on 19th November 2012. To induce the RF signal into the train's electrification and to monitor the induced signal, injecting and receiving coupling probes were assembled onto the high voltage DC power cable connected to the collector shoe, as shown.

The RF signal was generated by a signal source, and the inspection circuit in the train included a spectrum analyser. The signal source and the spectrum analyser were connected to injecting and receiving coupling probes, respectively. During the trial, a 50 MHz RF signal at 0 dBm (equivalent to 1 mW) was induced in the

train's electrification system using the injecting probe, and the induced signal was detected by the receiving probe and was clearly observed on the spectrum analyser. When the train was stationary, the detected RF signal remained stable. When the train was moving, the detected RF signal varied, a clear indication of the change in contact impedance between the third rail and the collector shoe due to the train's movement. The trial demonstrated the feasibility of the proposed method in monitoring the condition of the electrification system of a train without affecting its normal operation.

- 10 Experimentally, the power of the detected signal at 50 MHz is about -50 dBm (1×10^{-5} mW). For a 50 Ω system, the voltage induced will be less than 1 mV, which is 117.5 dB below (750,000 times smaller than) the 750 V operating voltage of the electrification system, which is too small to cause any safety concern. After consulting SMRT, the existing active communication frequencies used within the SMRT system are 68–88 MHz, 380–400 MHz, 470–490 MHz and 2.45 GHz. The 50 MHz RF signal does not fall into any of these frequency bands and is unlikely to cause any interference to the active communication frequencies.

References

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Claims

1. A method of detecting a fault in an electric railway system including a running rail, a power supply rail, and a rail vehicle moving along the running rail and receiving electric power from the power supply rail, the method including:
 - 5 generating a first alternating electric signal using an alternating signal generation unit mounted in the rail vehicle,
 - using a first inductive coupling unit mounted in the rail vehicle to inductively transmit the first alternating electric signal to a component of the rail
 - 10 vehicle which is electrically connected to a said rail, to create a second alternating electric signal in said component;
 - using a second inductive coupling unit mounted in the rail vehicle to inductively generate a third alternating electric signal from the second alternating electric signal; and
 - 15 performing a signal processing operation on the third alternating electric signal, and thereby detecting the fault.
2. A method according to claim 1 in which the component is electrically connected to the power supply rail.
- 20 3. A method according to claim 1 or claim 2 in which the second alternating electric signal flows in a circuit which further includes said running rail.
4. A method according to any preceding claim in which the second
- 25 alternating electric signal flows in a circuit which includes a collector shoe for collecting electric power from the power supply rail, an electric motor powered by said electrical power, a current return path and a capacitor provided on said current return path.

5. A method according to any preceding claim in which, upon detecting a fault, a report is generated including a location obtained from a location detection unit.
- 5 6. A method according to claim 5 in which the location detection unit is a GPS unit or a tachometer of the rail vehicle.
7. A method according to claim 5 or claim 6 in which the report is transmitted out of the rail vehicle before the rail vehicle has come to rest.
- 10 8. A method according to any preceding claim in which the signal processing operation includes comparing the amplitude of the third alternating electric signal to a first threshold, and generating a first fault detection signal if the amplitude is below the first threshold.
- 15 9. A method according to any preceding claim in which the signal processing operation includes comparing the amplitude of the third alternating electric signal to a second threshold, and generating a second fault detection signal if the amplitude is above the second threshold.
- 20 10. A method according to any preceding claim in which the first alternating electric signal is a radio frequency signal.
11. A method according to claim 10 in which the first alternating electric signal includes a component in the range in the range 300 kHz to 100 MHz.
- 25 12. A fault detection apparatus for detecting a fault in an electric railway system including a running rail, a power supply rail, and a rail vehicle for moving along the running rail and receiving electric power from the power supply rail, the apparatus being for location on the rail vehicle and including:
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an alternating signal generation unit for generating a first alternating electric signal,

a first inductive coupling unit for inductively transmitting the first alternating electric signal to a component of the rail vehicle which is electrically connected to a said rail, to create a second alternating electric signal in said component;

a second inductive coupling unit for inductively generating a third alternating electric signal from the second alternating electric signal; and

a signal processing unit for performing a signal processing operation on the third alternating electric signal, and thereby detecting the fault.

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13. An apparatus according to claim 12 having a report generation unit which, upon said signal processing unit detecting a fault, generates a report including a location obtained from a location detection unit.

15 14. An apparatus according to claim 13 including said location detection unit in the form of a GPS unit or tachometer.

15. An apparatus according to any of claims 12 to 14 further including a transmitter for wirelessly transmitting the report out of the rail vehicle.

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16. An apparatus according to any of claims 12 to 15 in which the signal processing unit is arranged to compare the amplitude of the third alternating electric signal to a first threshold, and generate a first fault detection signal if the amplitude is below the first threshold.

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17. An apparatus according to any of claims 12 to 16 in which the signal processing unit is arranged to compare the amplitude of the third alternating electric signal to a second threshold, and generate a second fault detection signal if the amplitude is above the second threshold.

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18. An apparatus according to any of claims 12 to 17 in which the alternating signal generation unit is operative to generate the first alternating electric signal as a radio frequency signal.
- 5 19. An apparatus according to claim 18 in which the radio frequency signal includes a component in the range 300 kHz to 100 MHz.