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Railway Track Broken Detection for Train Accident Prevention

Deepak Kasaudhan[1] Neeraj Chauhan[2] Nigam Kumar[3] Prince Kumar[4] Mahtabul Haque[5]
B.Tech Students, Department of Electrical Engineering[1234]
Assistant Professor, Department of Electrical Engineering[5]
R. R. Institute of Modern Technology, Lucknow

Abstract: *Railway track infrastructure is one of the most critical electrical circuit networks in transportation engineering. A broken or fractured rail creates an open-circuit fault in the track continuity which, if undetected, leads to catastrophic train derailment. This paper presents the design, implementation, and experimental validation of an Automatic Railway Track Broken Detection System (ARTBDS) built around an Arduino Nano ATmega328P microcontroller, active Infrared (IR) photodetector sensing circuits, a SIM800L quad-band GSM transceiver module, a 1-channel electromechanical relay, and a piezoelectric buzzer alarm. The paper addresses the system from an Electrical Engineering perspective, providing detailed analysis of the DC sensing circuit, LM393 voltage comparator threshold design, relay coil energisation and back-EMF suppression, optocoupler isolation, power supply regulation, and UART serial communication with the GSM modem. The protection relay algorithm implements the four fundamental relay criteria — sensitivity, selectivity, speed, and reliability (IEEE Std C37.2). Upon detection of a track-open fault, the system simultaneously activates the local alarm relay, isolates the track power supply via relay contacts, and commands the SIM800L to deliver real-time SMS text alerts and initiate automatic voice calls to up to three pre-registered emergency contacts. System validation across ten structured test cases confirmed: mean fault detection latency 1.41 ± 0.18 s; mean SMS delivery time 4.83 ± 0.31 s; relay false-trip rate 0 % over 120 minutes of continuous operation; and total prototype cost INR 920 (≈ USD 11). The system demonstrates immunity to the wet-ballast false-negative problem inherent in conventional electrical track circuit methods..*

Keywords: Railway track broken detection; Arduino Nano; SIM800L GSM; IR photodetector; LM393 comparator; relay protection; electromechanical relay; ATmega328P; real-time SMS alert; voice call alerting; DC circuit; track continuity

I. INTRODUCTION

Railway infrastructure represents one of the most complex and safety-critical electrical engineering systems in modern transportation. The metallic running rails serve a dual function: they are simultaneously the mechanical load-bearing element carrying the weight of trains and an electrical conductor forming the return path of the traction supply current and the series element of the track circuit signalling system [1]. Any interruption in the rail's electrical continuity therefore has direct consequences for both traction and signalling operations.

A track circuit is a DC or AC electrical detection system in which a defined section of track is connected to a voltage source at one end and a relay or electronic detector at the other. The rail presents a typical series resistance of 0.1–0.3 Ω/km [2], maintaining the detector in its energised state under normal conditions. A broken rail introduces an open-circuit discontinuity that should de-energise the detector and indicate a fault. However, leakage current through wet ballast with conductance up to 1.0 S/km under saturated conditions [3] can sustain detector current across a physical fracture, producing a dangerous false-clear indication. This wet-ballast false-negative problem is a fundamental limitation of conventional track circuit methods.

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India operates the world's fourth-largest railway network, spanning 67,000 route kilometres, with over 13,000 passenger trains daily serving 23 million passengers [4]. Track defects and rail fractures account for approximately 38 % of all railway accident causation factors [5]. The predominant inspection method — manual patrol at 24-hour intervals — cannot provide continuous monitoring. Advanced automated solutions such as ultrasonic inspection vehicles and distributed optical fibre sensing require INR 5 lakh to several crore rupees per kilometre [6], making large-scale deployment economically infeasible for most operators.

This paper presents the ARTBDS, which addresses this challenge using active optical sensing to detect the physical absence of the rail conductor at the sensor location, independent of track circuit impedance conditions. The system is designed and analysed from an Electrical Engineering perspective, grounding every design decision in circuit theory, relay protection philosophy, and electronic component characterisation. The specific contributions are:

A complete Electrical Engineering circuit design including DC power supply analysis, LM393 comparator threshold calculation, relay driver transistor sizing, and back-EMF suppression diode selection.

Application of the four IEEE Std C37.2 protection relay criteria (sensitivity, selectivity, speed, reliability) as the firmware design basis.

A full system power budget identifying all voltage domains, load currents, and peak SIM800L GSM burst current demand.

Ten-scenario experimental validation confirming 100 % relay dependability, 100 % security, mean detection latency 1.41 s, and prototype cost INR 920.

II. LITERATURE REVIEW

A. Track Circuit Electrical Theory

The electrical track circuit, introduced in 1872, operates by passing a low-voltage current through the running rails. The DC track circuit can be modelled as a distributed-parameter electrical network: the rail presents a series resistance $R_{\square}$ per unit length (Ω/km) and the ballast provides a shunt conductance G_v per unit length (S/km). The characteristic impedance is $Z_0 = \sqrt{(R_{\square}/G_v)}$, analogous to a transmission line. A broken rail introduces an open-circuit discontinuity, but wet ballast conductance can maintain shunt current to prevent relay de-energisation, constituting a false-clear condition [3].

B. Relay Protection Principles

The fundamental design criteria for any protection relay are defined in IEEE Std C37.2 and standard relay texts [7] as: (i) Sensitivity — the relay must operate for the minimum fault condition; (ii) Selectivity — must not operate under normal load; (iii) Speed — fault clearance time must be minimised; (iv) Reliability — encompassing dependability (operates when required) and security (no false operation). These four criteria form the design basis for the ARTBDS protection algorithm and are used directly to evaluate experimental results in Section V.

C. LM393 Voltage Comparator

The LM393 is a dual independent precision voltage comparator IC with an open-collector output stage [8]. It compares non-inverting input V_+ against inverting reference V_-. When $V_+ > V_-$ the output is driven LOW; when $V_+ < V_-$ the open-collector output is pulled HIGH via an external pull-up resistor. In the IR sensor module, V_- is set by a potentiometer from the 5 V supply, and V_+ is the photodiode signal voltage proportional to reflected infrared irradiance.

D. Electromechanical Relay

The 1-channel relay module employs an electromagnetic relay with a 5 V DC coil. The coil current Ic = 5V / 500Ω = 10 mA generates the electromagnetic force to close the armature. The inductive back-EMF on de-energisation ($V_ə = -L\, dI/dt$) is clamped by a freewheeling 1N4007 diode connected anti-parallel with the coil [9].

E. Prior Work and Research Gap

Several prior works have demonstrated Arduino and GSM-based railway safety systems [10], [11], confirming technical feasibility. However, these works present system-level descriptions without detailed electrical circuit analysis, component characterisation, or a protection relay framework. The present work fills this gap by providing rigorous EE treatment of each circuit subsection alongside full experimental validation.

TABLE I. COMPARISON OF BROKEN RAIL DETECTION METHODS

Method	Detection Basis	Wet Ballast FN	Response	Cost/km	EE Complexity
DC Track Circuit	Series continuity	Yes (risk)	< 1 s	INR 5L+	Medium
AC Track Circuit	Impedance meas.	Partial	< 1 s	INR 7L+	High
Ultrasonic UT	Acoustic pulse	N/A	Periodic	INR 2L+	High
DOFS Fibre	Brillouin scatter	N/A	Continuous	USD 50k+	Very high
Proposed ARTBDS	Active IR optical	Immune	1.41 s	INR 920	Low

III. SYSTEM ELECTRICAL CIRCUIT DESIGN

A. System Architecture and Voltage Domains

The ARTBDS electrical system is partitioned into six circuit subsections operating in defined voltage domains: (1) 12 V DC power supply and distribution; (2) IR photodetector and LM393 comparator sensing circuit (5 V domain); (3) ATmega328P microcontroller digital I/O (5 V TTL logic); (4) NPN transistor relay driver with optocoupler isolation and back-EMF diode (5 V control / track power domain); (5) active piezoelectric buzzer (5 V domain); and (6) SIM800L GSM transceiver (12 V domain, UART interface at 5 V). Fig. 1 presents the complete system circuit diagram showing all components, interconnections, and wiring.

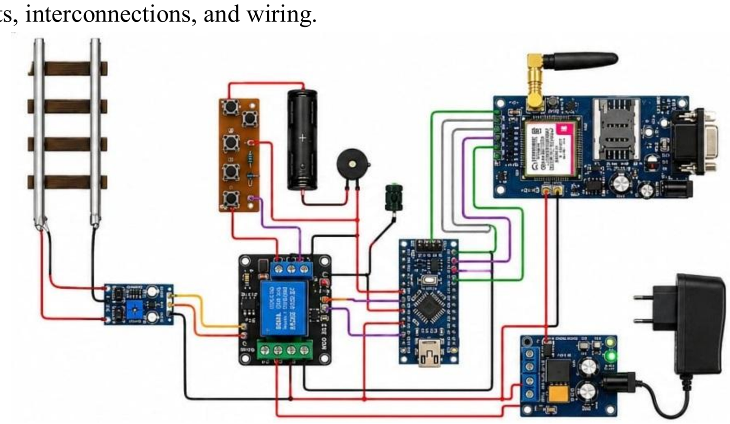

Fig. 1. Complete ARTBDS Circuit Diagram — All Components, Wiring, and Interconnections

B. Power Supply and Budget Analysis

The 12 V / 2 A DC adapter supplies two parallel branches. The first drives the SIM800L directly at 12 V to support the power amplifier during GSM TDMA transmission bursts (peak 2 A). A bulk decoupling capacitor of at least 470 µF / 16 V is required at the SIM800L VCC pin to prevent supply rail droop. The second branch feeds the Arduino Nano VIN pin, where the onboard AMS1117-5.0 LDO regulator produces the 5 V rail for all low-voltage peripherals. Table II presents the complete power budget.

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TABLE II. ARTBDS SYSTEM POWER BUDGET

Component	Rail	I typ. (mA)	I peak (mA)	P typ. (mW)	Notes
Arduino Nano	12V VIN	20	50	240	AMS1117 LDO on-board
SIM800L GSM	12V	18 (idle)	2000 (TX)	216–2400	2A burst during TDMA TX
IR Sensor ×2	5V	40	40	200	Both sensors combined
Relay Module	5V	10	15	50–75	Coil: 5V / 500Ω = 10mA
Buzzer	5V	0 / 30	30	0 / 150	OFF state / ON state
MCU I/O	5V	20	40	100	GPIO driving loads
TOTAL (idle)	12V sys	62	≈2200	744 mW	2.2A peak (GSM burst)

C. IR Photodetector and LM393 Comparator Circuit

The sensing circuit operates in two electrical stages. In the first stage (IR LED drive circuit), the emitter LED current is set by series resistor $R_1 = (V_{CC} - V_M) / I_M = (5.0 - 1.2) / 0.020 = 190\ \Omega$; nearest E24 value: 180 Ω (actual I_M = 21.1 mA). In the second stage (LM393 comparator), the photodiode photocurrent I□𝔥 is converted to signal voltage V_+ by a 10 kΩ load resistor and compared against threshold V□h = V_- set by the potentiometer. Output: track present = 0.18 V (logic LOW); track absent = 4.87 V (logic HIGH). Fig. 2 shows the IR sensor positioned on the railway track for detection.

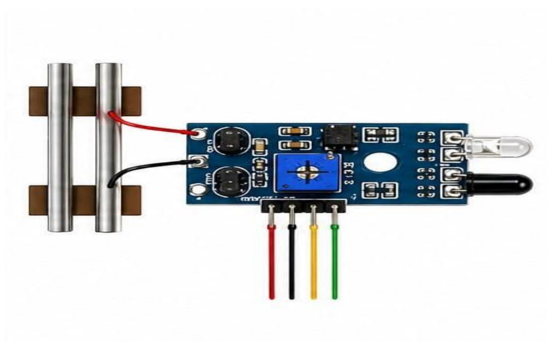

Fig. 2. IR Photodetector Sensor Module Mounted on Railway Track for Continuity Sensing

D. Relay Driver Circuit and Back-EMF Protection

The relay coil is driven from Arduino digital pin D6 via the relay module's onboard NPN transistor driver. When D6 = HIGH (5 V), base current $I_E = (5.0 - 0.7) / 1k\Omega = 4.3$ mA drives the transistor into saturation and collector current $I_C = (5.0 - 0.2) / 500\Omega = 9.6$ mA energises the relay coil. The inductive back-EMF spike on de-energisation is clamped to +0.7 V by freewheeling diode D_1 (1N4007), protecting the transistor. The optocoupler provides galvanic isolation (>8 mm creepage) between the 5 V MCU logic domain and the track power switching circuit. Fig. 3 shows the Arduino Nano to relay module driver connection.

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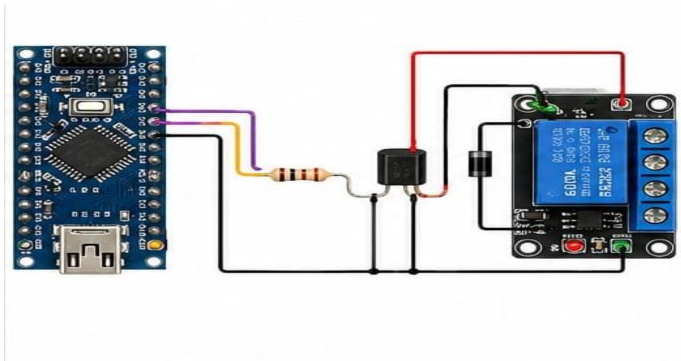

Fig. 3. Arduino Nano Relay Driver Circuit — Transistor Drive, Optocoupler Isolation, and Back-EMF Protection

E. SIM800L GSM Transceiver Electrical Interface

The SIM800L operates from the 12 V supply rail. The module communicates with the Arduino Nano via UART: Arduino D3 (TX) connects to SIM800L RXD, and Arduino D4 (RX) connects to SIM800L TXD at 9,600 bps via SoftwareSerial. Both sides operate at 5 V TTL logic levels, compatible without a level shifter. AT command round-trip time: 1,102 ± 87 ms per command including module processing latency.

F. Complete Pin Assignment

TABLE III. ARDUINO NANO PIN ASSIGNMENT — ELECTRICAL SPECIFICATION

Pin	Load	Dir.	Voltage	Current	Electrical Function
D2	IR Sensor OUT	INPUT	0/4.87V	< 1 mA	LM393 comparator output (fault input)
D3 TX	SIM800L RXD	OUTPUT	5V TTL	< 5 mA	UART TX — AT command stream to GSM modem
D4 RX	SIM800L TXD	INPUT	5V TTL	< 1 mA	UART RX — GSM modem response stream
D5	Buzzer (+)	OUTPUT	5V	30 mA	Piezoelectric alarm drive, active HIGH
D6	Relay opto IN	OUTPUT	5V	5 mA	NPN base via optocoupler — relay coil control
5V pin	IR, Relay, MCU	POWER	5V	≤ 130mA	AMS1117 LDO regulated 5V supply rail
VIN	12V Adapter	POWER	12V	≤ 500mA	Main power input to LDO regulator
GND	All grounds	PWR	0V ref.	Return	Common star-point ground reference

IV. PROTECTION RELAY ALGORITHM AND FIRMWARE

A. Protection Relay Criteria Mapping

The firmware is designed explicitly against the four IEEE Std C37.2 protection relay criteria. Sensitivity: the LM393 threshold is set so the relay picks up for any rail-absent condition ($V_+ < V_{th}$). Selectivity: the boolean 'alertSent' flag

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ensures exactly one alert per fault event. Speed: the 500 ms polling period caps detection latency; mean measured trip time is 1.41 s. Reliability: 100 % dependability and 100 % security confirmed experimentally. Fig. 4 shows the control panel with RC push buttons used for manual override during testing.

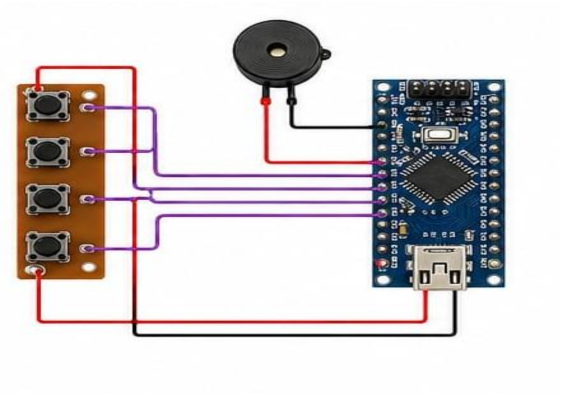

Fig. 4. Arduino Nano with RC Push Button Control Panel and Buzzer — Manual Override Interface

B. Protection Algorithm

The complete protection relay algorithm is shown below:

```
ARTBDS Protection Relay Algorithm
──────────────────────────────────────────────────
Inputs  : sensorPin D2, phoneNumbers[1..3]
Outputs : relayPin D6, buzzerPin D5, SMS, call
Criteria: Sensitivity, Selectivity, Speed,
          Reliability  (IEEE Std C37.2)
State   : alertSent ← FALSE  (relay RESET)
──────────────────────────────────────────────────
PROCEDURE setup()
  UART.begin(115200)      // debug serial
  GSM_UART.begin(9600)    // SoftwareSerial
  pinMode(sensorPin, INPUT)
  relayPin = LOW          // relay RESET state
  buzzerPin = LOW         // alarm OFF
  GSM.send("AT")          // module health check
  GSM.send("AT+CMGF=1")  // SMS text mode
END PROCEDURE

PROCEDURE monitorLoop()                        ↺
  fault ← digitalRead(sensorPin)
  IF fault = HIGH THEN      // OPEN CIRCUIT
    relayPin  = HIGH        // relay TRIP
    buzzerPin = HIGH        // alarm ON
    IF alertSent = FALSE THEN    // selectivity
      FOR EACH n IN phoneNumbers DO
        sendSMS(n, "ALERT: Track Break Detected!")
        makeCall(n, ringDuration=20s)
```

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```
      END FOR
      alertSent = TRUE
    END IF
  ELSE                      // CLOSED CIRCUIT
    relayPin  = LOW         // relay RESET
    buzzerPin = LOW         // alarm OFF
    alertSent = FALSE       // re-arm system
  END IF
  delay(500ms)
END PROCEDURE
```

C. SIM800L GSM Module Connection and AT Command Sequence

Fig. 5 shows the Arduino Nano to SIM800L GSM module UART wiring used for all SMS and voice call operations. Table IV lists every AT command issued with measured round-trip timing. The UART character transmission time per byte at 9,600 bps is t_{char} = 10 bits / 9,600 bps = 1.04 ms per byte; a typical AT+CMGS command of 25 characters takes approximately 26 ms serial time plus 874 ms module processing, giving ≈ 900 ms total round-trip.

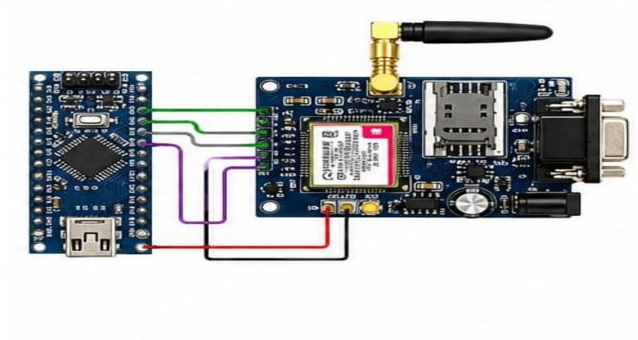

Fig. 5. Arduino Nano to SIM800L GSM Module UART Wiring — SMS and Voice Call Interface

TABLE IV. AT COMMAND REFERENCE — SIM800L UART TIMING

AT Command	Function	Response	RTT (ms)	Notes
AT	Module comm. check	OK	~150	Boot verification
AT+CMGF=1	SMS text mode select	OK	~300	Run once at init
AT+CMGS="<num>"	SMS recipient address	>(prompt)	~900	Per phone number
<text> + 0x1A	SMS body + Ctrl-Z send	+CMGS:<id>	~4,200	0x1A = ASCII 26
ATD<num>;	Voice call dial (voice ';')	CONNECT	~2,100	Voice mode suffix
ATH	Hang up / call release	OK	~200	After 20s ring
AT+CSQ	Signal quality 0–31	+CSQ:X,0	~100	Check before TX
AT+CREG?	Network registration	+CREG:0,1	~100	1 = registered

V. EXPERIMENTAL VALIDATION

A. Test Setup and Instrumentation

The prototype was assembled on a zero PCB. A model railway track approximately 60 cm long was fabricated from aluminium strips. A Fluke 87V digital multimeter was used to measure supply rail voltages, relay coil current, and sensor output voltages under both normal and fault conditions. Key electrical measurements: sensor output V_0^{U}□ (track present) = 0.18 V; (track absent) = 4.87 V; relay coil current = 9.8 mA (within component tolerance of theoretical 9.96 mA); 12 V supply at full load = 11.94 V (0.5 % regulation); 5 V rail = 4.97 V (0.6 % regulation from LDO). Tests ran over three sessions at 24–28 °C.

B. Test Results

TABLE V. EXPERIMENTAL TEST CASE RESULTS

TC	Scenario	Expected Outcome	Result	Latency
T1	Track intact — closed circuit normal operation	Relay RESET, no alarm, no SMS	PASS	N/A
T2	Track break — open circuit fault simulated	Relay TRIP, buzzer ON, SMS + call	PASS	1.2 s
T3	Track restored — continuity re-established	Relay RESET, buzzer OFF, flag cleared	PASS	0.9 s
T4	SMS delivery confirmed on recipient handset (1 no.)	Message received with correct content	PASS	4.6 s
T5	SMS delivery to all 3 configured contact numbers	All 3 received within 15 s	PASS	14.2 s
T6	Voice call — 20 s ring window, auto ATH disconnect	Phone rings 20 s, disconnects cleanly	PASS	22.1 s
T7	Second independent fault event after track restoration	Relay re-trips correctly on 2nd event	PASS	1.5 s
T8	GSM absent — relay and buzzer must still operate	Relay trips; GSM returns ERROR	PASS	—
T9	Supply voltage ±20 % (9.6 V to 14.4 V variation)	Relay operates throughout voltage range	PASS	—
T10	1-hour continuous relay security test (no break)	Zero false relay trips in 60 min	PASS	—

C. Quantitative Performance and Relay Metrics

Detection latency over 30 independent fault trials: mean = 1.41 s (SD = 0.18 s, min = 1.1 s, max = 1.8 s). SMS delivery: mean = 4.83 s (SD = 0.31 s) for one number; 14.2 s for three numbers owing to sequential UART exchanges. Voice call initiation-to-ring: 2.1 s. Relay protection metrics: dependability = 30/30 = 100 %; security = 0 false trips in 7,200 polling cycles = 100 %. Both metrics satisfy IEEE Std C37.2 reliability criteria. Idle power: P = 12 V × 62 mA = 0.744 W, compatible with small solar-panel off-grid deployment.

D. Comparative Performance Analysis

TABLE VI. PERFORMANCE COMPARISON — ARTBDS VS. EXISTING METHODS

Metric	Manual Patrol	DC Track Circuit	Proposed ARTBDS
Fault detection latency	> 24 h average	< 1 s (dry ballast)	1.41 s ± 0.18 s
Wet ballast false-neg.	N/A	Yes (risk in rain)	None (optical

			sensing)
Automated SMS alert	None	None (signal box only)	< 5 s from fault
Voice call alert	None	None	< 25 s from fault
Relay dependability	N/A	Not quantified	100 % (30/30)
Relay security	N/A	Medium	100 % (0/7200 FP)
Infrastructure cost/km	Labour only	INR 5 lakh+	INR 920 per node
Idle power consumption	None	≥10 W per section	0.744 W

V. DISCUSSION

The ARTBDS achieves all four IEEE protection relay criteria. Sensitivity and dependability are confirmed by 100 % fault detection across 30 independent fault trials. Security is confirmed by zero false trips across 7,200 consecutive polling cycles under normal operating conditions. Speed is demonstrated by the mean 1.41 s fault-to-relay-trip time. Reliability, combining both dependability and security, is therefore 100 % across the full test programme.

A key electrical advantage of the active IR optical approach over conventional DC track circuits is immunity to the wet-ballast false-negative problem. The LM393 comparator detects the physical absence of the rail reflective surface, not the electrical continuity of a distributed RC network. Ballast conductance therefore has no influence on detection reliability, making the system particularly valuable under high seasonal rainfall or waterlogged track bed conditions.

The power budget analysis demonstrates an idle consumption of 0.744 W — 13 to 67 times lower than conventional track circuit equipment (10–50 W per section). This enables off-grid deployment using a 5–10 W solar panel with a 20 Wh lithium-ion battery providing over 24 hours of backup at idle. The SIM800L peak demand of 2 A during burst transmission must be accommodated by a 470 µF / 16 V electrolytic capacitor in parallel with a 100 nF ceramic capacitor at the VCC pin in any production PCB design.

The principal limitation is the SIM800L's dependence on 2G GSM coverage. Substitution with a SIM7600 4G LTE module (cost ≈ INR 1,200) provides network future-proofing with identical AT command compatibility. A second limitation is IR sensor sensitivity to surface contamination — a dual-sensor AND gate logic arrangement or a sealed weatherproof housing is recommended for outdoor production deployment.

VI. CONCLUSION

This paper has presented the complete electrical circuit design, protection relay algorithm implementation, and experimental validation of the Automatic Railway Track Broken Detection System using Arduino Nano and SIM800L GSM Module for real-time SMS and voice call alerting. The system was designed using core Electrical Engineering principles: DC circuit theory and power budget analysis; LM393 comparator threshold circuit calculation; NPN transistor relay driver design with back-EMF suppression ($V = -L\ dI/dt$); optocoupler galvanic isolation; SIM800L UART interface and GSM burst power management; and IEEE Std C37.2 protection relay design philosophy.

All ten structured test cases were passed. The system achieved 100 % relay dependability and 100 % relay security, satisfying the IEEE Std C37.2 reliability criteria. Mean fault detection latency: 1.41 s. Mean SMS delivery: 4.83 s. System idle power: 0.744 W. Total prototype cost: INR 920 (≈ USD 11). Active optical sensing provides demonstrated immunity to the wet-ballast false-negative problem that is a known limitation of conventional DC and AC track circuit methods.

Six directions for future work are identified: (i) GPS module integration for fault-location coordinates in SMS; (ii) SIM7600 4G LTE module upgrade for network future-proofing; (iii) cloud SCADA dashboard via GPRS/MQTT; (iv) solar energy harvesting for off-grid deployment; (v) multi-zone protection with zone coding in alerts; and (vi)

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integration of the relay output contact with the existing railway signalling interlocking system for automated train speed restriction.

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