Indonesian Journal of Electrical Engineering and Computer Science
Vol. 39, No. 2, August 2025, pp. 807~820
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v39.i2.pp807-820

The design of an electronic load for mitigating transient overvoltage in the track circuits of railway signaling systems

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Article Info

Article history:

Received Nov 13, 2024
Revised Mar 17, 2025
Accepted Mar 26, 2025

Keywords:

Failure modes and effects analysis
Railway signalling system
Safety electronic load suppression
Track circuit
Transient overvoltage

ABSTRACT

The research presented the design of safety electronic load suppression (SELS) for mitigating transient overvoltage in the track circuits of railway signaling systems while changing the track occupancy in the track circuits of the signaling system that caused damage to the BR966F2 relay. The analysis of the average failure of the electronic devices, the failure modes and effect analysis (FMEA), and the performance test of electronic devices were conducted. and the performance test of electronic devices were conducted. which can control the operation with 2oo3 processing mode (two out of three voting) under the series circuits pattern to resolve the damage caused by the application. Results illustrated that the mean operating time of the SELS between failures was 9,399 hours. In addition, regarding the performance of the electronic load for mitigating transient overvoltage of 1 kV at 31.4 V and overvoltage 50 VDC at 178.6 °C within 83 seconds at 35.4 V. Additionally, the SELS could function adequately without failure or causing any damage. Therefore, the SELS was more reliable.

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1. INTRODUCTION

State-of-the-art technology is crucial for the country's development as it steers the economy, particularly the electricity and electronics industry, which plays a significant role in conceiving innovations that are the key components of other products: electric appliances, communication devices, energy management systems, and smart vehicles. In the 4.0 era, these technologies have been upgraded to be smarter, connect with the internet, and more compact to fulfill user needs. Nevertheless, using complex tools and devices affects the electrical system in case of electrical quality issues, such as transient overvoltage or electrical system faults. As a result, electronic devices may be damaged despite installing preventive tools. For this reason, the electrical quality analysis and improvement must consider the local state to mitigate the tentative risk and damage. The railway signaling system is a crucial electronic system that enhances speed and safety by managing train movement on designated tracks [1], [2]. It displays train track occupancy so that the engine driver foresees the state of the ahead track before deciding to stop, reducing speed, or adjusting the direction appropriately for safe, quick, and efficient transport [3]-[7]. The screen displaying the train track occupancy is shown in Figure 1.

In the electric system, the voltage waveform, electric current, and frequency can change from the normal state, according to IEEE Std.1159, because of natural phenomena, electrical faults, the switching of devices, the use of non-linear devices, and incorrect grounding [8]-[11]. All causes lead to issues with electric power quality systems that damage electronic devices and affect the railway signaling system. Therefore, the analysis to resolve the problems with the electric power quality must consider the actual state. A gas discharge tube (GDT), a preventive device, is used to mitigate the impact of the transient overvoltage problem caused by lightning or the switching of the track occupancy equipment in the railway signaling system. However, some electric and electronic devices are damaged, as shown in Figure 2.

Figure 1. Screen showing the train track occupancy

Figure 2. The burning BR966F2 relay from the transient overvoltage

Transient overvoltage affects the function of the BR966F2 relay. During the operation, the heat accumulates at the relay's coil, and the coil insulation deteriorates. Consequently, it burns due to the transient overvoltage while changing to the non-occupancy status [12]-[16], as shown in Figure 3.

Figure 3 shows the transient overvoltage state while changing the non-occupancy status in the track circuit. When the train departs from the track, the receiver displays the track clear. Therefore, there is the transient overvoltage at 1.1kV and the wave at 136/284µS. Since the transient overvoltage issues are still unsolved, the electric power quality improvement analysis must rely on the actual state. Transient overvoltage causing damage to the BR966F2 relay in the railway signaling system hampers the train operation command. The statistics of the causes of railway signaling system disruption from 2022 to 2023 are in Figure 4.

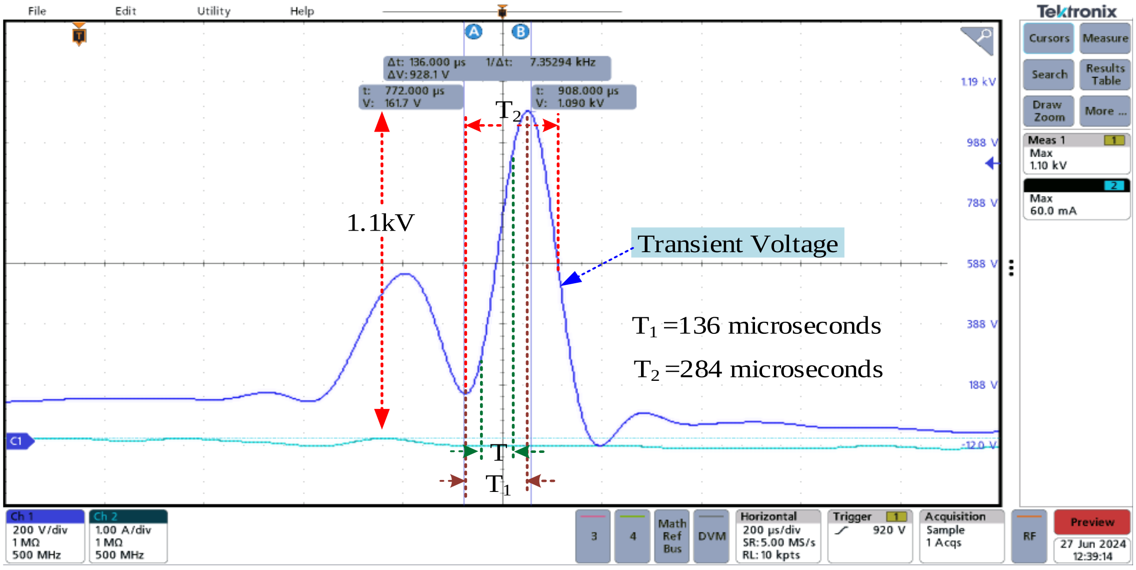

Figure 3. Transient overvoltage while changing to non-occupied status

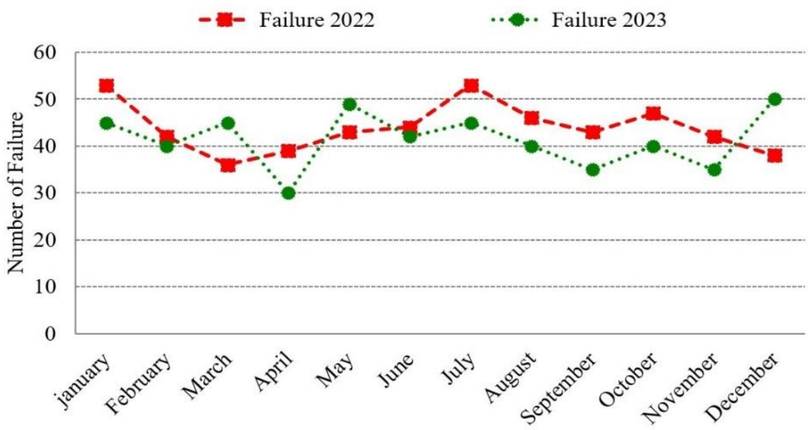

Figure 4. Statistics of the causes of railway signaling system disruption

Track occupancy or line capacity, which includes the stop time at the station to allow the train on the opposite track to pass, and the buffer time for the operation, the delay schedules, accounts for 40% of the operation time. The calculation of the line capacity using the method of the State Railway of Thailand as shown in the (1) [5].

$$\text{Line capacity} = \frac{T_d}{T+t} \times 70\% \quad (1)$$

Electrical quality pertains to the track circuits impeding train operation commands. Research and data collection on transient overvoltage in the track circuits of railway signaling systems, which causes damage to the BR966F2 relay, was conducted [17]-[19]; it detects the overvoltage, the frequency to transient overvoltage, and the reduction of transient overvoltage using the safety transient voltage suppressors (STVS). However, it does not demonstrate a permanent solution or long-term practice.

This study proposed designing an electronic load to reduce transient overvoltage in the track circuits of railway signaling systems. This aims to mitigate the damage to electrical appliances and electronics connected to the track circuits resulting from the electrical quality issue to minimize the damage to the BR966F2 relay. The insulate gate bipolar junction transistor (IGBT) has replaced the surge protection device. The transient voltage surge (TVS) was the electronic load with high watt power to reduce the transient overvoltage under the safety failure mode to handle the transient overvoltage. which is in the safety failure mode for maintaining stability and more system reliability with the failure modes and effect analysis (FMEA), the safety integrity level (SIL) of monitoring and command via the operation conditions using the interlocking method of the signaling system is improving, which corresponds with the IEC 16508-4 standard of the State Railway of Thailand.

2. PRINCIPLE OF THE TRACK CIRCUIT FUNCTION

The track circuit exhibits the track occupancy at the time. The function of the electric circuit is separated with insulation. One side of the track is a power supply, and the other is the signal receiver with the BR966F2 relay. The track circuit shows track occupancy. Voltage abnormality and signal detection are sent to the BR966F2 relay of the track circuit to detect the track circuit occupancy [20]-[26]. In the normal operational state, the power supply distributes direct current power (DC track circuit) to the inductor track, with a voltage of 15.6Vp, to transmit the signal through the track to the receiver. If the receiver receives a signal, it indicates the track is clear. If a train comes in between the transmitter and receiver, the axle and wheel are iron inductors, so the electric system cannot connect, or a short current occurs. As a result, the voltage on the track decreases and cannot be transmitted to the receiver since the current at the axle and the wheel flows back to the power supply. It indicates the track is occupied in this block, or there is the occupancy of the track circuit, as shown in Figure 5.

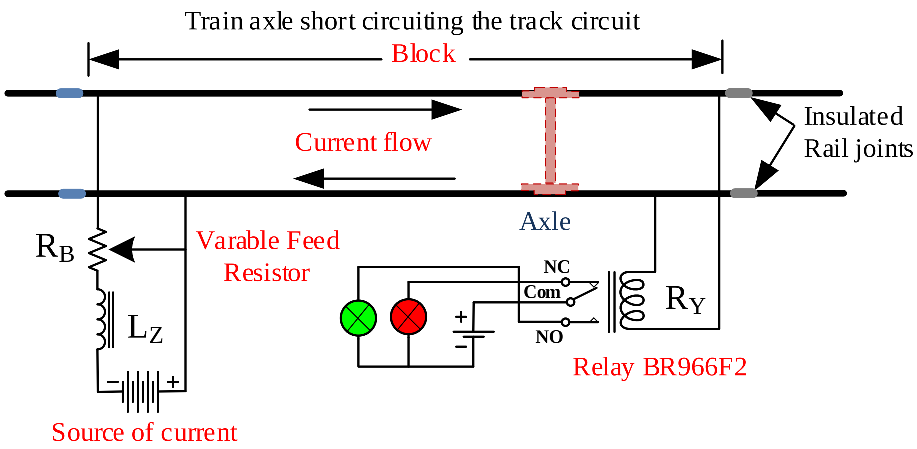

Figure 5. Fundamental principle of the track circuit

The track circuit's fundamental principle indicates that the resistance value significantly impacts its function within the signaling system. The ballast resistance is adjusted to ensure the appropriate current for the quality of the BR966F2 relay. The ballast resistance circuit is shown in Figure 6.

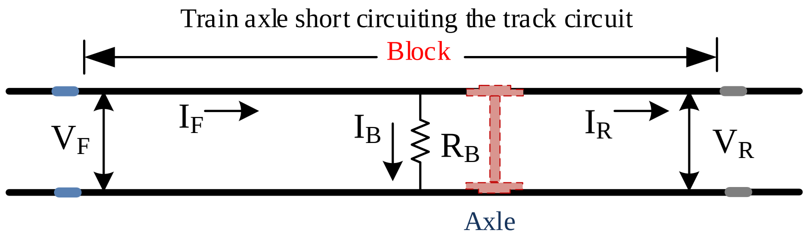

Figure 6. Ballast resistance circuit

The calculation to determine the ballast resistance (R_B):

$$R_B = \frac{E_B}{I_B} \quad (2)$$

where:

$$E_B = \frac{1}{2}(V_F + V_R) \tag{3}$$

which makes the R_B to,

$$R_B = \frac{\frac{1}{2}(V_F+V_R)}{I_F-I_R} \tag{4}$$

where:

$$I_F = \frac{V_{VR}}{R_{VR}} \tag{5}$$

and,

$$R_R = \frac{V_{VR}}{R_{VR}} \tag{6}$$

The appropriateness of the track circuit's accurate operation can be determined. If it does not follow the conditions, the distance of the track circuit is adjustable to gain the appropriate ballast resistance for the correct operation of the railway signaling system.

3. PRINCIPLE OF DESIGNING THE TRANSIENT OVERVOLTAGE PROTECTION SYSTEM

3.1. Relationship between the surge protection devices

The current surge protection device (SPD) used in the railway signaling system protects the overvoltage from lightning impulse or surge voltage (V_S) to eliminate the energy from the lightning getting through the track circuit using the GDT. Surge voltage (V_S) gets through the impedance of the rail (Z_R), and a voltage drop occurs (Vcl_GDT). However, according to IEEE Std 62.41, as shown in Figure 7, it does not cause any damage [27]-[29], as shown in Figure 7.

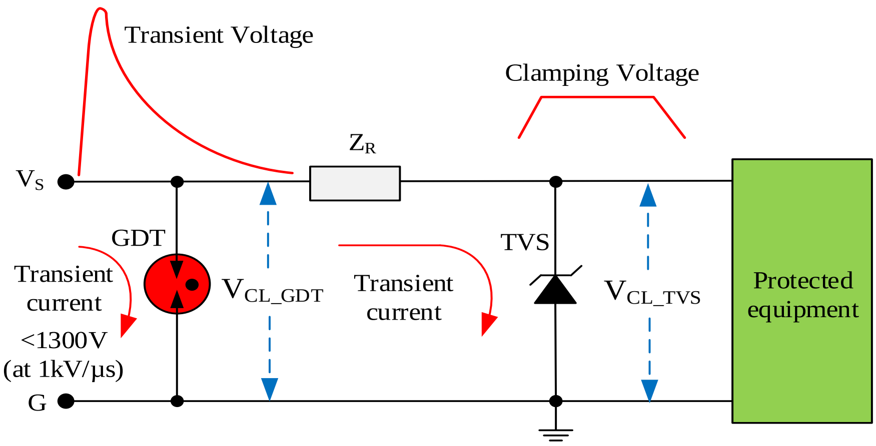

Figure 7. Relationship between the SPD

Even though the relationship of the SPD with the GDT is arranged, the surge voltage (V_S) in the railway signaling system and the voltage drop (V_{cl_GDT}) are still at a high rate. Further, there is the transient overvoltage while changing the track clear status due to the signaling system malfunction. Therefore, installing one set of GDT surge protection devices cannot effectively prevent possible damage to the BR966F2 relay if the overvoltage remains or is lower than the operational level. The application of transient voltage suppression diode (TVS), the quick-response equipment to mitigate the transient overvoltage, enables the clamping voltage (V_{CL_TVS}) to prevent the voltage from being over the TVS standard, as shown in the (7)-(9):

$$V_{TVS} \approx V_{CL\_TVS} \quad (7)$$

Calculation of maximum pulse current (I_{TVSD}):

$$I_{TVS} = \frac{V_S}{Z_R + Z_{TVS}} \quad (8)$$

Calculation of clamping voltage (V_{CL_TVS}):

$$V_{CL\_TVS} = \frac{V_S}{Z_R + Z_{TVS}} \quad (9)$$

The relationship of the surge prevention device enables the clamping voltage in the railway signaling system as the (10):

$$V_{CL\_GDT} < V_{CL\_TVS} \quad (10)$$

Although using TVS responds to the transient overvoltage quickly, and the clamping voltage (V_{CL_TVS}) is at the acceptable level that will not damage the BR966F2 relay, its durability is very low. The operation of the railway signaling system may malfunction if the device is impaired and finally leads to operation disruption.

3.2. Designing the device to mitigate the transient overvoltage using the electronic load

The device's design mitigates transient overvoltage by using the electronic load, the electronic switch pulling the current to the ground, and adopting the IGBT and TVS to reduce the overvoltage. Consequently, the new device, the transient voltage suppression IGBT device (TVS_{IGBT}) was invented to facilitate the IGBT's function as the electronic load to mitigate the transient overvoltage [18], [19], as shown in Figure 8.

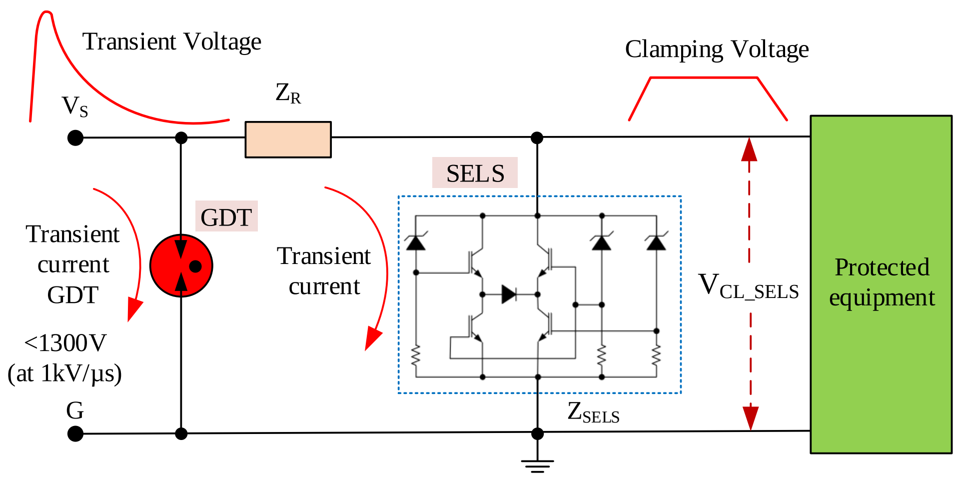

Figure 8. Diagram block of all transient overvoltage devices with the electronic load

3.3. Designing safety electronic load suppression (SELS)

The design of SELS is to mitigate the transient overvoltage from the change of track clear status after the failure of the railway signaling system. The SELS is a series circuit with the 2oo3 processing mode (Two out of Three Voting) [30], [31], as shown in Figure 9.

The design of SELS consists of TVS_1, TVS_2, and TVS_3, which detect the transient voltage to control the electronic load device. $IGBT_1$, $IGBT_2$, $IGBT_3$, and $IGBT_4$ work as the electronic load to control the voltage and direct the current to flow to the grounding; its function is similar to the quality of the TVS to reduce the transient overvoltage.

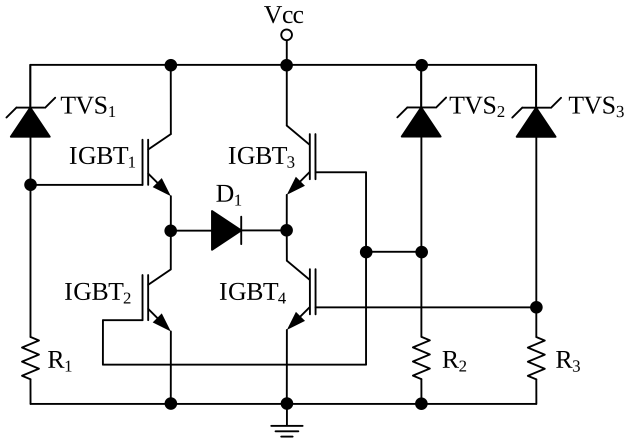

Figure 9. Safety electronic load suppression circuit

The design of SELS is to outline the circuit to include the fail-safe to prevent harmful failure by the voter logic block 2oo3 or the fail detection 2 out of 3. Regarding the detection mode of the TVS in the SELS, the voltage is released through the TVS (Let Through Voltage: V_{lt_TVS}) to drop at the resistor (R); it is the trigger voltage of IGBT (Vg) to direct the current flow of the IGBT. The design of the SELS with the voter logic block 2oo3 comprises AND logics and OR logics, as shown in the (11):

$$V_{g\_SELS} = (TVS_1 \times TVS_2) + (TVS_2 \times TVS_3) + (TVS_1 \times TVS_3) + (TVS_1 \times TVS_2 \times TVS_3) \quad (11)$$

The critical component of the possibility for error and circuit failure is the number of devices in the circuit. Fewer devices will reduce errors and failures efficiently. For this reason, the function of SELS with the two sets of STVS connected in the series circuit would maximize the SELS's resistance to the transient overvoltage and expand the transient current via the SELS in different functions of all mode operation for more reliability. Additionally, it would allow the leakage current to flow to the ground (LC). The current flow direction is as shown in the (12).

$$I_{LC_{SELS}} = (IGBT_1 \times IGBT_2) + (IGBT_3 \times IGBT_4) + (IGBT_1 \times IGBT_4 \times D_1) + (IGBT_1 \times IGBT_2 \times IGBT_3 \times IGBT_4 \times D_1) \quad (12)$$

The condition of the 2oo3 failure check is to detect two out of three failures so the current flows through the IGBT and the clamping voltage at the SELS of the designed device. In Figure 9, the transient overvoltages for each SELS circuit are detailed. The first SELS circuit includes IGBT1 and IGBT2; the second consists of IGBT3 and IGBT4. The third circuit features IGBT1, IGBT4, and D1, while the fourth circuit incorporates IGBT1, IGBT2, IGBT3, IGBT4, and D1. The characteristics of the transient overvoltage drop at the first SELS circuit of IGBT1 and IGBT2 are shown in Figure 10.

Besides, the calculation of the average failure of the electronic device is the reliability prediction of the electronic device components. The device's total failure rate can be calculated using (13):

$$\lambda_{P\_SELS} = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E \_Failures/10^6\ Hours \quad (13)$$

the SELS total failure is:

$$\lambda_{SELS\_2oo3} = \lambda_{IGBT} + \lambda_{TVS} + \lambda_D + \lambda_R \_Failures/10^6\ Hours \quad (14)$$

the average time of the SELS failure is:

$$MTTF_{SELS} = \frac{1}{\lambda_{SELS\_2oo3}} \_Failures/10^6\ Hours \quad (15)$$

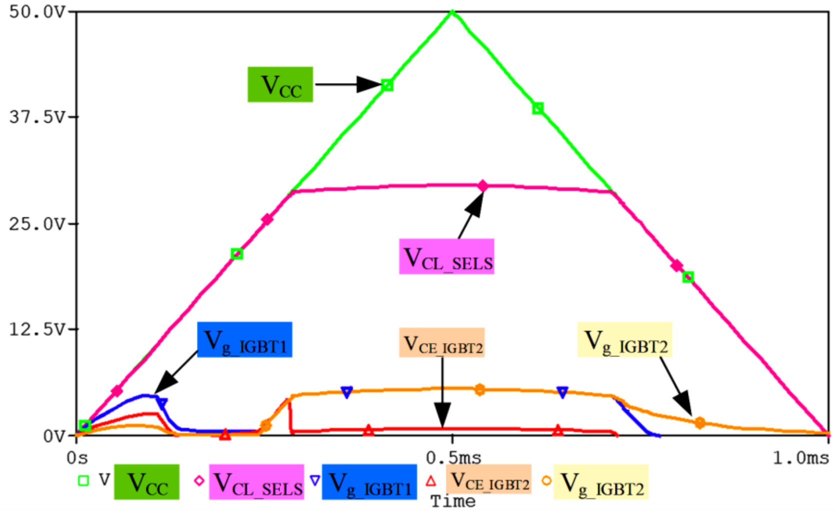

Figure 10. Characteristic of the transient overvoltage drops at the SELS of the first set

4. PERFORMANCE TEST RESULT OF THE ELECTRONIC LOAD DEVICE

The SELS performance test comprises three parts: reliability prediction for electronic components, FMEA [32]-[34], and the overvoltage wave performance test. The transient overvoltage is 1kV, and the wave is 136/284µS, as shown in Figure 3. The test to determine the SELS's voltage drop is exhibited in Figure 11.

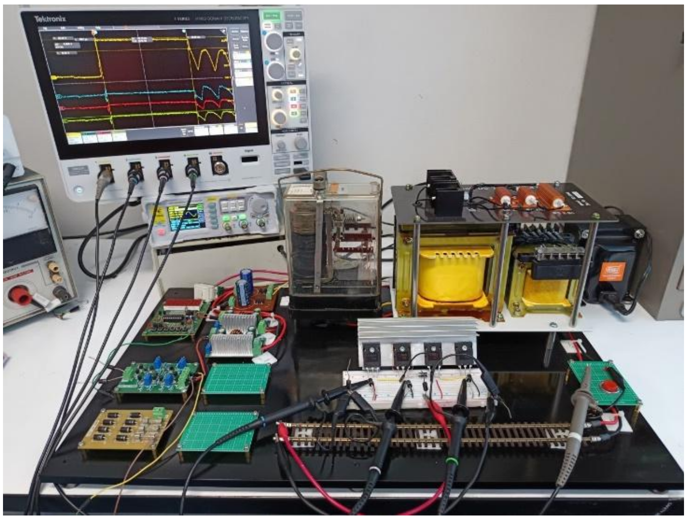

Figure 11. SELS performance test

4.1. Reliability prediction for electronic components

It is the crucial component of the equipment selection process and the mean operating time between failures (MTBF), as shown in Table 1.

Table 1. Failures of the electronic equipment

No.	Notation	Components	Failure rate (10^6h)
1	λ_p	Diode	0.9728
2	λ_p	TVS	0.256
3	λ_p	IGBT	26.1
4	λ_p	Resistor	0.081

Table 1 illustrates the reliability prediction for electronic components or the failure of the SELS. The failure rate of the SELS is from the equation:

$$\lambda_{SELS\_2oo3} = 106.3838\_Failures/10^6\ Hours \tag{16}$$

The calculation to find the mean time before failures is from the equation:

$$MTTF_{SELS} = 9{,}399\ Hours \tag{17}$$

The mean time before failure obtained from the reliability prediction or the SELS failure is 9,399 hours.

4.2. Failure modes and effects analysis

The FMEA is conducted with the SELS as the tool to indicate the safety fail analysis to determine damage prevention. In accordance with the IEEE C62.41.1:2002 standard [11], there are three fundamental analysis principles of the failure mode: Short, Open, and Degraded (outside of the specification limits). The analysis result would ensure the invented circuit will function in fail-safe mode, as shown in Table 2. The FMEA of the SELS in the railway signaling system analyzes the failures and effects that tentatively occur with any parts of the circuit, such as short circuits and burning. These issues cause the circuit to malfunction. The solution to the problems would accommodate the availability and secure usability.

Table 2. Failure modes and effects analysis results

Devices	Failure mode	Effect of the SELS	Effect of failure	Potential effects
TVS_1	Open circuit	Output Vdc present	b	Δ
	Short circuit	Output Vdc present	b	Δ
TVS_2	Open circuit	Output Vdc present	b	Δ
	Short circuit	Output Vdc present	b	Δ
TVS_3	Open circuit	Output Vdc present	b	Δ
	Short circuit	Output Vdc present	b	Δ
R_2	Open circuit	Output Vdc present	b	Δ
	Short circuit	Output Vdc present	b	Δ
	R_2*2	Output Vdc present	b	Δ
	R_2*0.5	Output Vdc present	b	Δ
$IGBT_1$	Open circuit	Output Vdc present	b	Δ
	Short circuit	Output Vdc present	b	Δ

Note) (*0.5), (*2), Short and Open refer to the standard values of IEC 61496-1: (a): Output is reduced to 0, (b): Normal output, (c): Abnormal output Δ no significant consequences ▲ abnormal condition

4.3. Electronic load performance test

4.3.1. Performance test with the 1 kV transient overvoltage wave

The SELS performance test model uses the transient overvoltage wave at 1 kV. and the waveform slope at 136/284µS involves several dimensions of function and safe durability [35]-[37]. The voltage drop test results (V_{CL_SELS}) are shown in Figure 12.

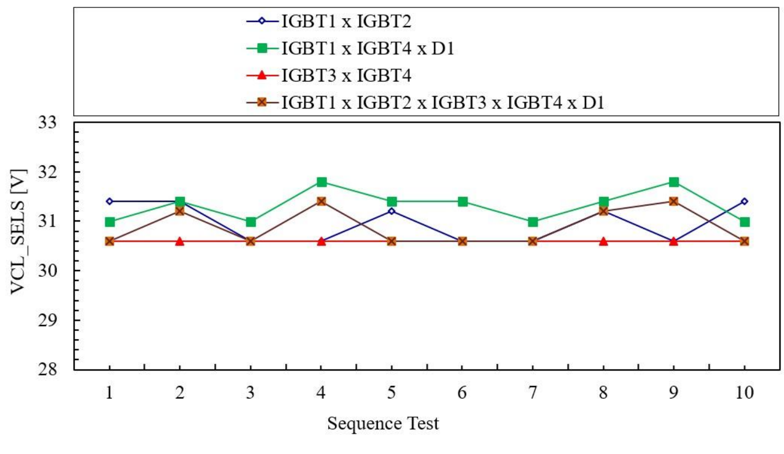

Figure 12. Test result of clamping voltage on the electronic load (V_{CL_SELS})

Installing the electronic load to mitigate the transient overvoltage in the railway signaling system's track circuit reduces the transient voltage by eliminating the transient current power via the SELS to the grounding system. Consequently, the clamping voltage on the SELS controls the transient overvoltage that flows into the track circuit to avoid damage to the BR966F2 relay. Only the clamping voltage with the crested wave remains and will lose 31.4V, as shown in Figure 13.

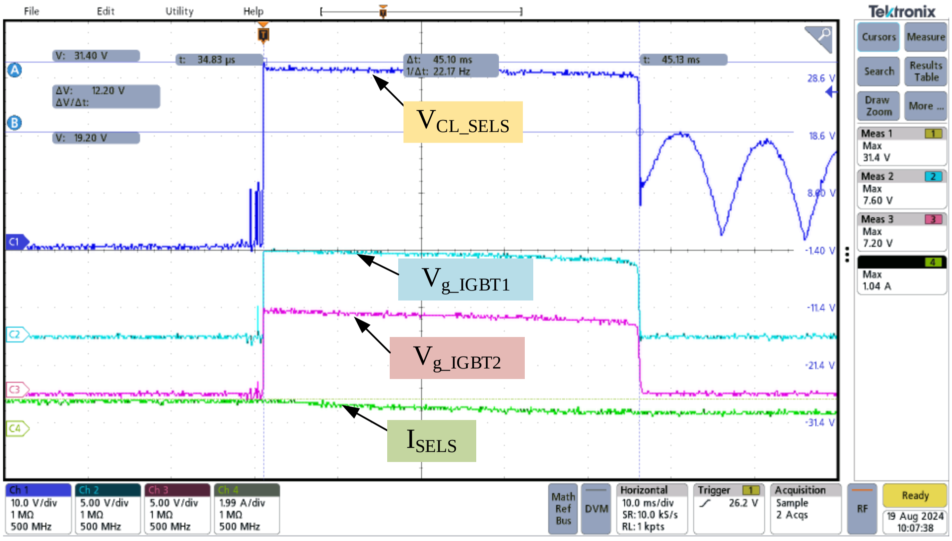

Figure 13. Quality of clamping voltage on the electronic load

4.3.2. Performance test with the overvoltage at 50V$_{DC}$

The electronic load performance test for mitigating the overvoltage is conducted to test the durability of the SELS when the overvoltage at 50 V$_{DC}$ is supplied to the track circuit [38]-[44]. Findings show current flows through the SELS within 83 seconds. As a result, the temperature of the SELS increases to 178.6 °C, which is the same resistance quality as the IGBT. In addition, the SELS can work commonly without any failures or damages to the entire circuit. Therefore, the circuit gains more reliability. The thermal of the electronic load for mitigating the overvoltage at 50 V$_{DC}$ is shown in Figure 14.

Figure 15 demonstrates the quality of the clamping voltage on the electronic load at 35.4 V to mitigate the overvoltage at 50 V$_{DC}$. It shows that the electronic load's performance mitigates the transient overvoltage at 1 kV with the wave slope 136/284 µS and the overvoltage at 50 V$_{DC}$ without compromising the SELS's function.

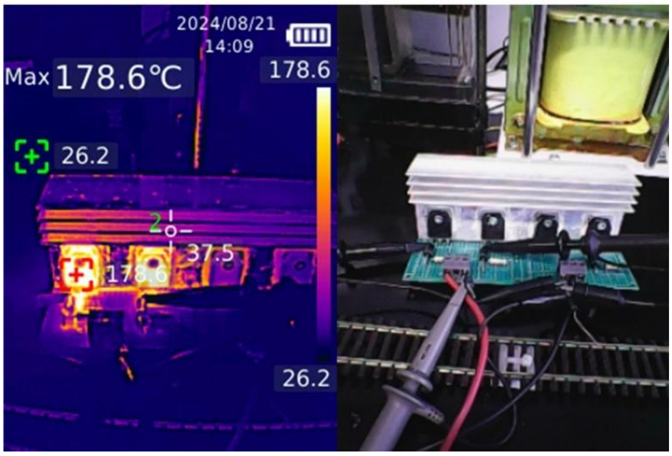

Figure 14. Thermal of the electronic load for mitigating the overvoltage at 50 V$_{DC}$

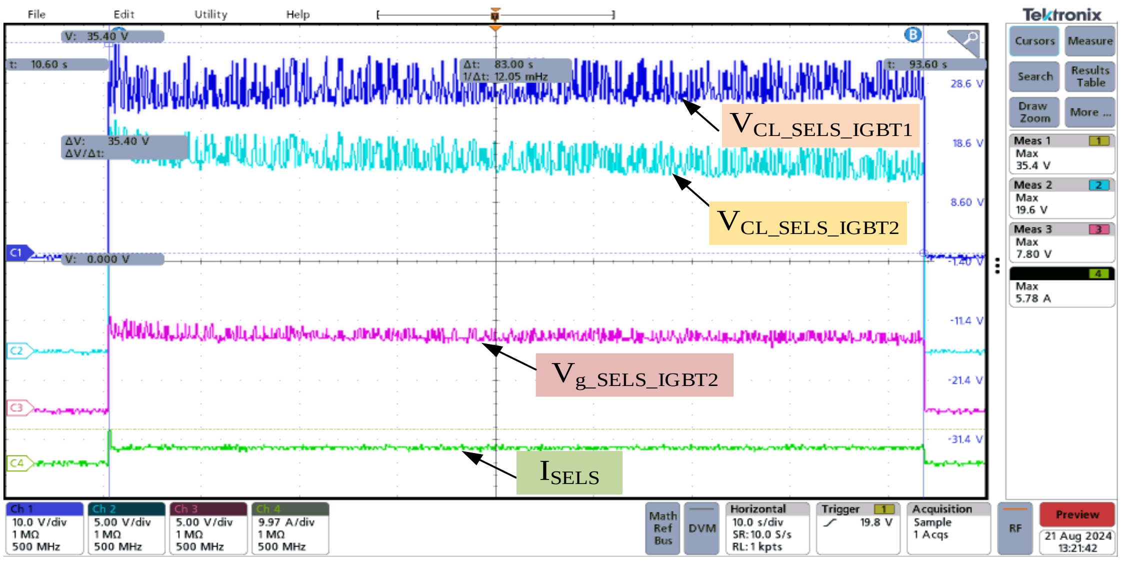

Figure 15. Clamping voltage on the electronic load for mitigating the overvoltage at 50 V_{DC}

5. CONCLUSION

This study proposed the design of SELS in the track circuits of railway signaling systems, which changes the occupancy status and damages the BR966F2 relay. The design of SELS involves developing an electronic load using the IGBT instead of TVS, which can control the operation with 2oo3 processing mode (two out of three voting) under the series circuits pattern to resolve the damage caused by the application. The average failure of the electronic devices was analyzed using the FMEA, and the electronic load efficiency was tested. According to the reliability or SELS failure prediction, the mean time before failure and damage was 9,399 hours. In addition, the performance of the electronic load with a transient overvoltage of 1 kV mitigated the transient overvoltage by eliminating the transient current power via the SELS to the grounding system. Consequently, there was a clamping voltage of 31.4 V on the SELS. Additionally, the durability of the SELS was tested by supplying the overvoltage at 50 V_{DC} to the track circuit. Results showed that it could reduce the overvoltage of 50 V_{DC} at 178.6 °C within 83 seconds at a voltage of 35.4 V without compromising the normal function of the SELS or causing failure or damage to the overall system and the BR966F2 relay. Thus, the design of compact and durable SELS with high-watt power could reduce the 1 kV transient overvoltage, and 50 V_{DC} overvoltage would maximize the reliability of the track circuit of railway signaling systems.

ACKNOWLEDGEMENT

The author would like to offer sincere gratitude to Mr. Sommai Jitpakdee, Chief Engineer of the Signalling and Telecommunication Department (S&T), and State Railway of Thailand (SRT) for providing the information for the completion of this research.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research adheres to ethical standards relevant to the field. For studies involving human or animal subjects, ethical approval from appropriate bodies has been obtained and documented.

DATA AVAILABILITY

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