Safety hysteresis comparator design for transient overvoltage detection

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ABSTRACT

This research introduces a safety hysteresis comparator that detects transient overvoltage in the track circuit relay interlocking of railway signaling system. This overvoltage is caused by voltage faults transmitted through the electric conductor on the track feed unit to the receiver equipped with the track relay, which acts as the occupied track circuit controller. The circuit was designed using safety system design principles and concepts. Findings illustrated that the transient overvoltage detection of the safety hysteresis comparator in the track circuit activated when the input voltage (V_{in}) was higher than the high hysteresis signal level (V_{hyst_H}). When V_{in} was less than low hysteresis signal level (V_{Vhyst_L}), the output voltage (V_o) state was low. Otherwise, it was high. The hysteresis voltage was 4.4 V. The installation of the transient overvoltage detector in the track circuit was to monitor the transient overvoltage fault in the track circuit and to confirm that the hysteresis comparator was in the safety failure mode, which was the safety function for the track circuit to be compliant with the IEC 61800-5-2 standard to ensure the system stability and reliability. It would maximize the performance of the controlling function and commanding of train arrangement of State Railway of Thailand (SRT).

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1. INTRODUCTION

The railway signaling system is the figure or audio symbol [1], [2]. The signaling system plays a crucial role in ensuring safe transportation. The system components must work efficiently to provide precise signals to the driver, enabling them to make informed decisions about slowing down, stopping or navigating through the route ahead. Additionally, other essential controlling equipment must be installed to support the signaling system [3], further enhancing the efficiency of the transport operation. The railway signaling system is shown in Figure 1.

All relay interlocking has been developed for computer-based interlocking [4]–[7], consisting of a signal displayed on a monitor and the control panel at the signal control tower. The signaling system equipment must undergo a safety analysis and risk assessment following IEC 62425:2007 [8], [9]. When the train does not occupy the track, the normal condition is displayed on the monitor by a white route, and the signal post shows red. When an adjacent station releases a train to enter the station for a pick-up and drop-off or proceed to the terminal station, the turnout position and the safety of the track circuit when the train is passing must be verified. Once safety is ensured, the route panel's monitor route will turn green, and the red signal will turn green. When the train passes the track circuit, the status will change to indicate occupied; the green route will change to red. When the train has passed the track circuit, the panel will return the route to white, and the signal will turn back into a red signal. The track circuit is the system that monitors the train's location by applying the short circuit principle when stepping on the wheel axle [10]–[16]. When no train is on the track, electricity is supplied from the track circuit's power supply through the BR966F2 relay [17]. When the train is operating on the track circuit, the wheels and wheel axles are short-circuited in the track circuit. Consequently, the voltage supplied to the track relay disappears, and the train's location in the track circuit can be determined by displaying the information at the controlling center. The status of track occupied display by red Routh on station monitoring operator (SMO) at the Bangkok Signal Control Tower (BSCT), Central Signal Maintenance Division (CSMD), Signaling and Telecommunication Department (S&T), and State Railway of Thailand (SRT) is shown in Figure 2.

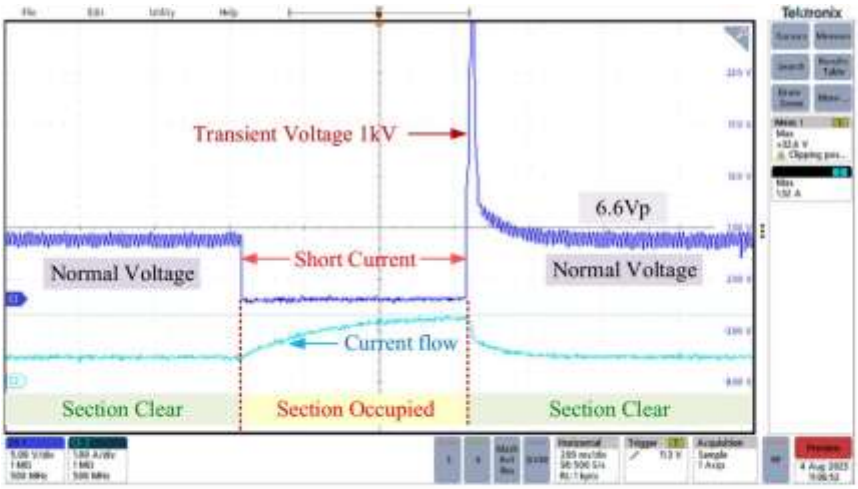
The power supply of the occupied track circuit in the signaling system is a center-tapped full-wave rectifier [18], [19]; it is the circuit consists of two diodes, D_1 and D_2, connecting with the center-tapped transformer that the inductor filter or choke filter is the filter to smooth the electric current. It is an efficient filter that reduces the high-frequency noise to prevent electromagnetic interference (EMI) from the electric current [20], [21]. The occupied track circuit in the signaling system is shown in Figure 3.

During track occupancy, the voltage of the electric system of the track circuit is zero. When a train moves out of the electric circuit, transient overvoltage occurs at 1 kV [22]–[27], when changing to non-occupancy. The transient voltage in the track circuit while the train moves out of the block is a transient response from the accumulated energy in the track circuit's inductor. When departing from the block, the electricity returns to normal and the relay is activated. Consequently, there is a transient voltage at 1 kV. In Figure 4 the voltage wave on the track during train departure and the transient voltage wave in the track circuit are illustrated in Figures 4(a) and 4(b).

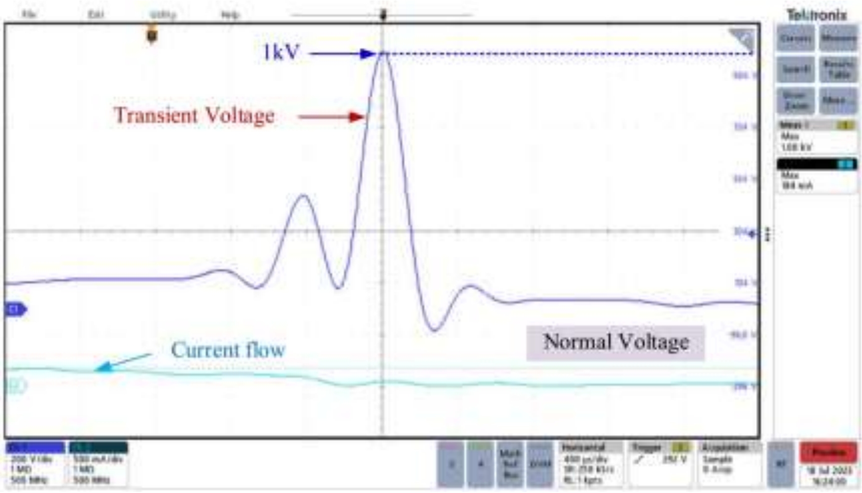
Figure .1 Signal post)starter w/call-on signal)

Figure 2. Monitor displaying train occupation on station monitoring operator (SMO)

Figure 3. The occupied track circuit in the signaling system



(a)



(b)

Figure 4. Transient voltage wave in the track circuit (a) voltage on the track while the train departs from the block and (b) transient voltage in the track circuit

The transient overvoltage that is the cause of damage to the BR966F2 relay has been used in the track circuit relay interlocking of the railway signaling system hinders the train's operational command. The statistics of the disruptions of the railway signaling system during 2019-2021 are shown in Figure 5. To ensure smooth train operations, certain factors must be considered. These include the line capacity, the time required for a train from the opposite track to pass through [28], [29], the stop time at the station, and buffer time for any delays. After the train passes through the track circuit daily, electric quality changes in a transient overvoltage form. As a result, the BR966F2 relay is burnt, as shown in Figure 6.

This research presented the safety hysteresis comparator for the transient overvoltage detection in the railway signaling system track circuit when the train leaving the track circuit resulted in the transient overvoltage and the damage of the track relay. The design of the safety hysteresis comparator for transient overvoltage detection is to detect the voltage fault in the track circuit to obtain the data to find the solution to prevent damage to the track circuit [30]. The safety hysteresis comparator (SHC) consists of a compact and simple transistor to count the fault of DC voltage supply in the track circuit of the railway signaling system that requires controlling stability and reliability. The SHC is a self-diagnostic circuit with a failure modes and effect analysis (FMEA) that checks and delivers a command via the interlocking condition with the safety integrity level (SIL) for higher system reliability [31]–[35].

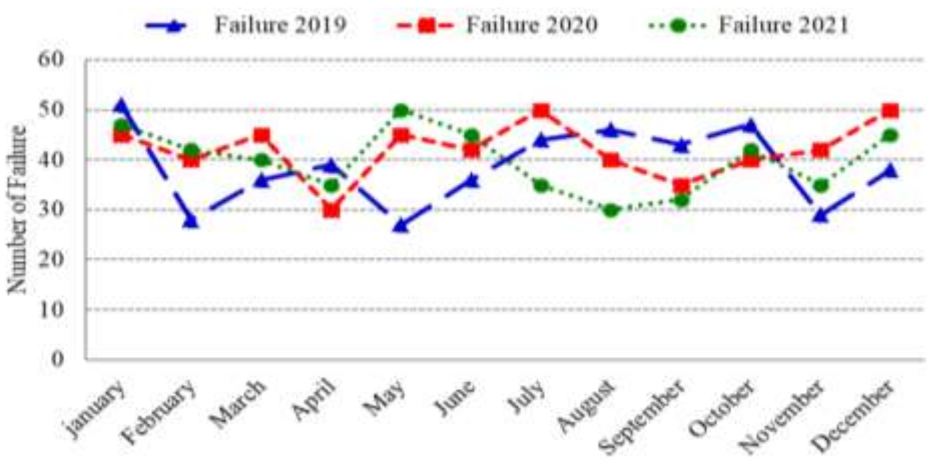


Figure 5. Statistics of the railway signaling system disruptions

Figure 6. A burnt BR966F2 relay caused by the transient overvoltage

2. DESIGNING THE SAFETY HYSTERESIS COMPARATOR CIRCUIT

The safety hysteresis comparator for transient overvoltage detection in the track circuit relay interlocking of the railway signaling system is designed based on fail-safe modes in the safety system [36]–[38]. This circuit is designed to eliminate input signal oscillation, which reduces the likelihood of detection circuit failure. Using an op-amp as the hysteresis comparator can make it difficult to identify faults. Therefore, this research developed a hysteresis comparator using a transistor. For this reason, this research designed the hysteresis comparator using a transistor [39]–[44]. The design of the hysteresis comparator circuit uses the resistor ($R_{Feedback}$:R_F) to feedback the output voltage (V_o) to combine with the input signal (V_{in}). The hysteresis comparator circuit function has feedback of the output voltage of the transistor to enable it as a switch to allow the feedback voltage ($V_{Feedback}$:V_F) to increase the input voltage (V_{in}). The concept of the block diagram of the hysteresis comparator is shown in Figure 7.

In Figure 7, the function represents an operational amplifier (op-amp) that compares electrical voltage between two voltage levels: the high hysteresis signal level (V_{hyst_H}) and the low hysteresis signal level (V_{hyst_L}). The feedback voltage (V_F) passes through the resistor (R_F), which enables the hysteresis comparator circuit. The design of the hysteresis comparator circuit uses the transistor to feedback the output voltage (V_o) to combine with the input signal [45], [46]. It utilises three transistors to control the circuit: Q_1 is the feedback loop of the output signal, Q_2 and Q_3 are the oscillator circuits, and Q_4 is the inverter circuit, as shown in Figure 8.

Since the hysteresis comparator circuit function has feedback of the output voltage (V_o) of the transistor Q_4 to the bias at the base of transistor Q_1 to enable it as a switch to allow the feedback voltage (V_F) to increase the input voltage (V_{in}). The transistor receives the bias all the time until the input voltage is lower than the low hysteresis signal level)V_{hyst_L}(. The equation for calculating the high hysteresis signal level (V_{hyst_H}) at A, which has the component of three resistors (R_1, R_2, and R_3) connected in a series circuit, is as (1) and (2).

$$V_A = V_{cc}\left(\frac{R_3}{R_1+R_2+R_3}\right) \quad (1)$$

$$V_{hyst\_H} = V_{cc}\left(\frac{R_3}{R_1+R_2+R_3}\right) + V_{ECQ2} \quad (2)$$

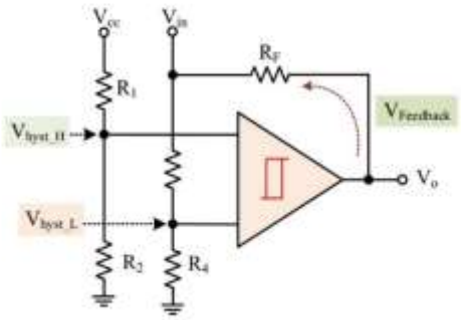


Figure 7. The concept of the hysteresis comparator block diagram

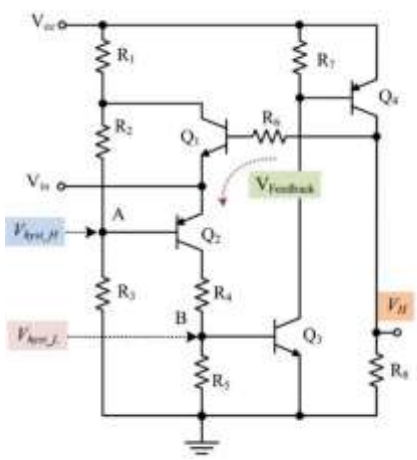


Figure 8. Voltage function of the hysteresis comparator circuit

Furthermore, the calculation of the high hysteresis signal level)V_{hyst_H}(can determine the high hysteresis signal level ($V_{ref\_hyst\_H}$), as (3).

$$V_{hyst\_H} = V_{ref\_hyst\_H} - V_{ECQ2} \quad (3)$$

The high hysteresis signal level) V_{hyst_H} (puts the output voltage (V_o) in the high state, and the feedback voltage)V_F (increases the input voltage)V_{in}(. The feedback voltage)V_F(can be calculated from (4).

$$V_F = V_{in} + V_{BEQ1} + V_{ECQ2} \quad (4)$$

The calculation to determine the low hysteresis signal level)V_{hyst_L}(is done by finding the input voltage)V_{in}(that combines with the clamping voltage at the transistor Q_1)V_{EBQ1}(. The determination of the low hysteresis signal level) V_{hyst_L} (at B that has three resistances R_4 and R_5 as the voltage divider circuit shown in (5) and (6).

$$V_B = V_{in}\left(\frac{R_5}{R_4+R_5}\right) \quad (5)$$

$$V_{hyst\_L} = V_{in}\left(\frac{R_5}{R_4+R_5}\right) + V_{BEQ1} + V_{ECQ2} \quad (6)$$

In addition, the calculation of the low hysteresis signal level)V_{hyst_L} (by determining the reference voltage of the low hysteresis signal level ($V_{ref\_hyst\_L}$) is:

$$V_{hyst\_L} = V_{ref\_hyst\_L}\left(\frac{R_5}{R_4+R_5}\right) \quad (7)$$

When the input voltage)V_{in} (has a higher voltage than the high hysteresis signal level)V_{hyst_H}(, the state of the output voltage)V_o(is high. When the input voltage V_{in} has a lower voltage than the low hysteresis signal level)V_{hyst_L}(, the state of the output voltage)V_o (is Low, as:

$$V_{in} \geq V_{hyst\_H} = High \quad (8)$$

$$V_{in} \leq V_{hyst\_L} = Low \quad (9)$$

The graph of voltage characteristics of the hysteresis comparator circuit displays the high hysteresis signal level)V_{hyst_H} (and the low hysteresis signal level)V_{hyst_L}), as shown in Figure 9.

In Figure 9, the input voltage (V_{in}) ranges up to the low hysteresis signal level (V_{hyst_L}) point B, as per (6), which triggers the Q_3 transistor. As a result, the NPN transistor operates at a base-emitter voltage (VBE) of approximately 0.7 V, allowing electrical current to flow through it, and remains in a saturated state. This causes the output voltage V_o to be high. When the input voltage decreases, the low hysteresis signal level)V_{hyst_L}) at point B also decreases. This happens because the feedback voltage (V_F) increases the Q_3 base-emitter voltage, leading to the Q_3 transistor being in a cutoff state. To cut off the Q_3 transistor, the input voltage must decrease, and the voltage at point B must be lower than 0.5V (V_{BE}<0.5 V). When the input voltage (V_{in}) is lower than the output voltage (V_o), it is called the hysteresis voltage (V_{hyst}), as shown in the graph. The difference of hysteresis voltage)V_{hyst}(of the hysteresis comparator-from the voltage and pulse width detection of the hysteresis comparator circuit, the difference between the high hysteresis reference voltage)$V_{ref\_hyst\_H}$ (and the low hysteresis reference voltage) $V_{ref\_hyst\_L}$ (are shown in Figure 10.

Figure 10 shows intersecting lines of the input voltage (V_{in}) and the output voltage (V_o) that represent the reference voltage of the hysteresis voltage)V_{hyst}(. The front of the pulse wave of the input voltage (V_{in}) serves as the reference voltage for the high hysteresis signal level ($V_{ref\_hyst\_H}$). In contrast, the back of the pulse wave of the input voltage (V_{in}) acts as the reference voltage for the low hysteresis signal level ($V_{ref\_hyst\_L}$). The graph of input and output characteristics of the hysteresis voltage with the high hysteresis reference voltage)$V_{ref\_hy\ st\_H}$ (and the low hysteresis reference voltage) $V_{ref\_hyst\_L}$ (is shown in Figure 11.

The calculation of the difference hysteresis voltage)Vhyst(of the hysteresis comparator is as (10).

$$V_{hyst} = V_{ref\_hyst\_H} - V_{ref\_hyst\_L} \quad (10)$$

Using the hysteresis comparator circuit in pulse width detection via the transient overvoltage period in the track circuit can eliminate input signal oscillation and reduce detection errors. The transistor-based safety hysteresis comparator design facilitates damage checks using FMEA.

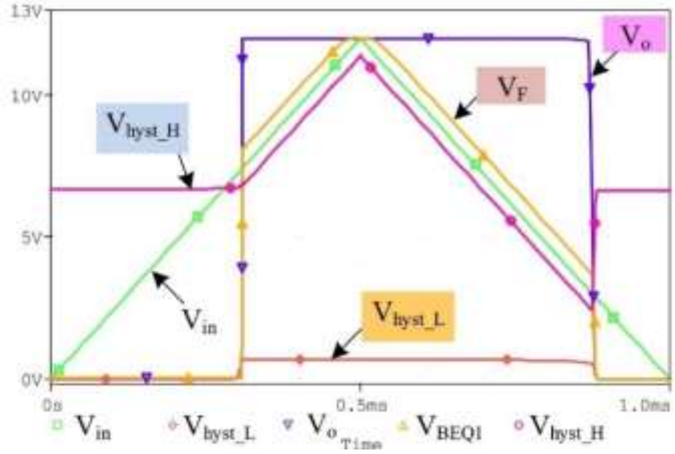


Figure 9. The graph of the hysteresis signal level

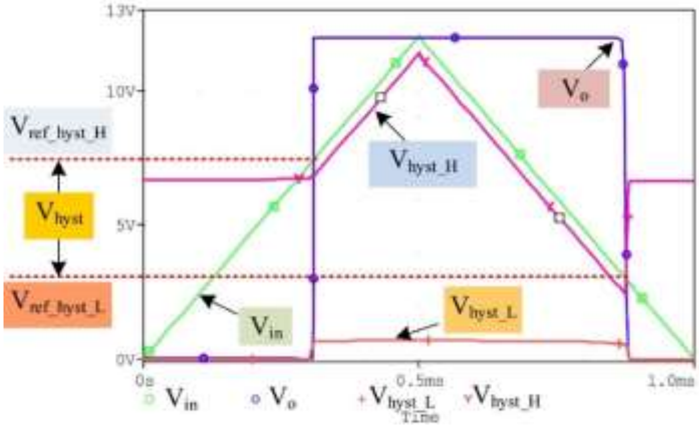


Figure 10. Voltage and pulse width detection of the hysteresis comparator circuit

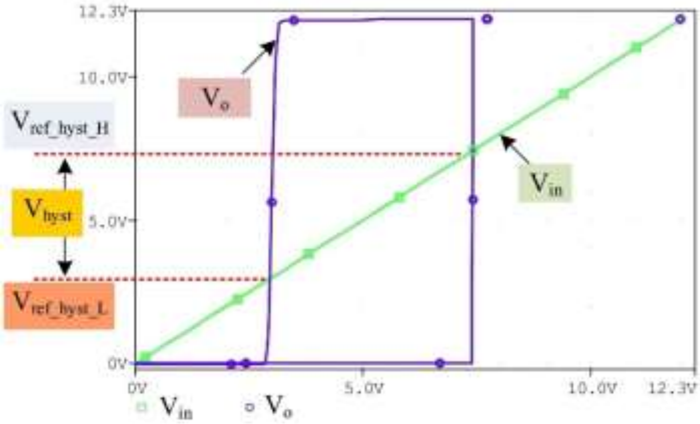


Figure 11. The graph of input and output characteristics of the hysteresis voltage

3. CIRCUIT TEST RESULT

3.1. Test of transient overvoltage detection circuit using the safety hysteresis comparator

The efficiency test of the safety hysteresis comparator for transient overvoltage detection in the track circuit of the railway signaling system is shown in Figure 12. The efficiency test results of the safety hysteresis comparator for transient overvoltage indicated that the normal voltage of the track circuit relay Interlocking of the railway signaling system was 6.6 V. The operational function value was set at +10%, or 7.2 V, to prevent the malfunction from noise. The hysteresis signal level at different points is shown in Figure 13.

When the input voltage V_{in} was higher than the high hysteresis signal level (V_{hyst_H}), the output voltage ($V_{o)}$ was in a high state. When the input voltage ($V_{in)}$ was lower than the low hysteresis signal level V_{hyst_L}, the output voltage was at a low state. The high hysteresis signal level reference voltage $V_{ref\_hyst\_H}$ was 7.24V, and the low hysteresis signal level reference voltage $V_{ref\_hyst\_L}$ was 2.84 V. Thus, the difference in the hysteresis voltage V_{hyst} was 4.4 V, consistent with the design, as shown in Figure 14. The monitor in the Signaling and Telecommunication Department of the State Railway of Thailand displayed the number of transient overvoltage events in the track circuit of the railway signaling system, as shown in Figure 15.

Figure1 2. The efficiency test of the safety hysteresis comparator

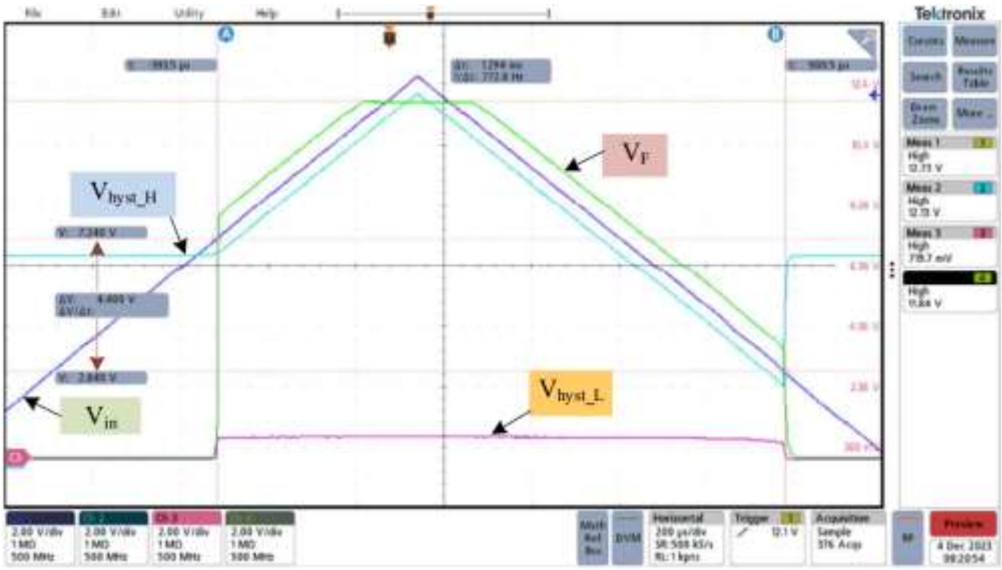


Figure 13. The graph of hysteresis signal level at different points

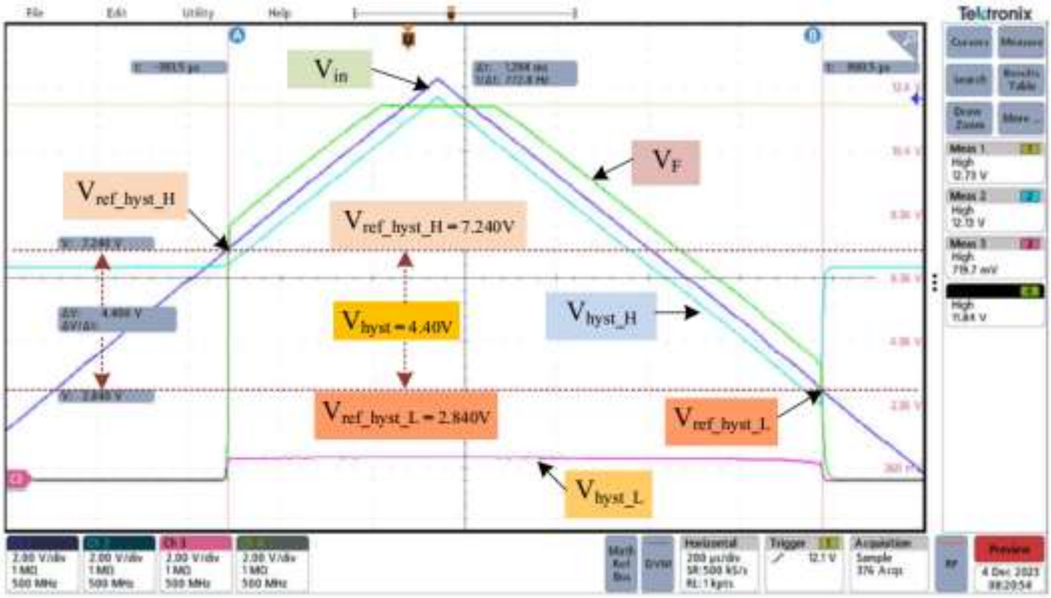


Figure 14. Graph of hysteresis signal level reference voltage and output hysteresis voltage

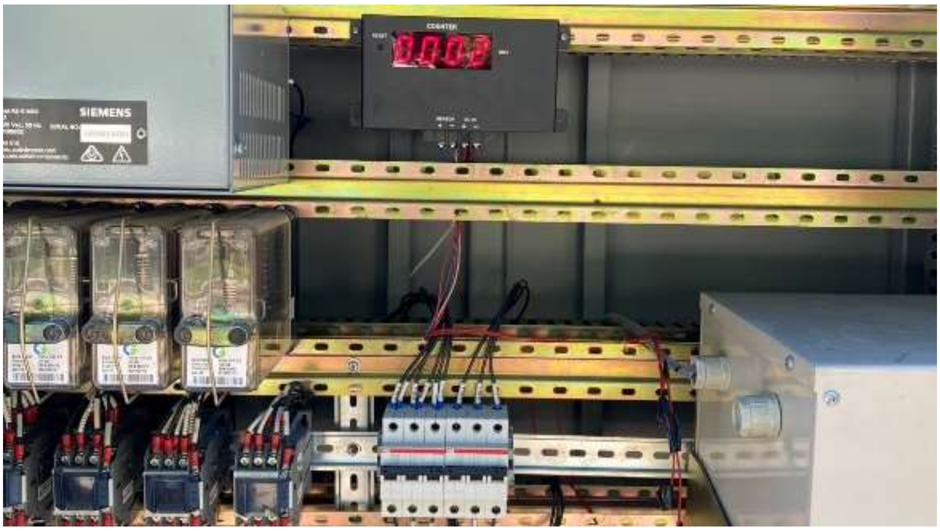


Figure 15. The installation of the transient overvoltage detection in the track circuit relay Interlocking of the railway signaling system

3.2. Analysis of damage characteristics and possible effects

The safety hysteresis comparator's fail-safe design operation was analyzed by the FMEA tool to simulate potential failure and its effects on safety [47]–[50]. When a failure occurs in any part of the circuit, the safety hysteresis comparator will activate the fail-safe function to prevent damage to the system. The analysis principle is defined in the IEC standard numbered 61496-1. In circuit simulations, various standards and specifications may be utilized, including different resistor values. The circuit's functionality can be analyzed by simulating various error scenarios, such as opening or closing circuits, doubling or halving the value, and more. When conducting experiments, we avoided using IC op-amps due to the difficulty in simulating internal circuits. During simulations, the effects of damage were analyzed to identify problems and preventive measures, as detailed in Table 1. From the FMEA of the transient overvoltage detection with the safety hysteresis comparator, the possible damages to the circuit included the short circuit, burning, and other issues. These problems are the cause of failures. The solution to problems is required to apply the designed circuit safely.

Table 1. Results of failure modes and effects analysis (FMEA)

Devices	Failure mode	Effect of the hysteresis comparator	Effect of failure	Effect of counter circuit
R_1	Open circuit	Hysteresis voltage reduced	2	O
	Short circuit	Hysteresis voltage reduced	2	O
	R_1*2	Hysteresis voltage increase	2	O
	R_1*0.5	Hysteresis voltage reduced	2	O
R_2	Open circuit	Hysteresis voltage increase	2	O
	Short circuit	Hysteresis voltage reduced	3	O
	R_2*2	Hysteresis voltage increase	2	O
	R_2*0.5	Hysteresis voltage reduced	2	O
R_3	Open circuit	No output signal	1	O
	Short circuit	Hysteresis voltage increase	2	O
	R_3*2	Hysteresis voltage reduced	2	O
	R_3*0.5	Hysteresis voltage increase	2	O
Q_1	Open circuit	Hysteresis voltage reduced	2	O
	Short circuit	Hysteresis voltage increase	3	O

Notes Change of decrease value (R_n*0.5) Change of increase value (R_n*2) referred from the standard measurement.
)1 (No output signal)2 (normal output)3 (abnormal output but detected
O: No significant consequences of counter circuit ∆: significant consequences of counter circuit

4. CONCLUSION

This study introduces a design for a safety hysteresis comparator that can detect transient overvoltage in the track circuit relay interlocking of a railway signaling system. This is necessary because of a design failure that damaged the BR966F2 relay. The circuit for detecting transient overvoltage includes a signal processing circuit, a transistor hysteresis comparator, and the track circuit relay interlocking of the railway signaling system. The hysteresis comparator is a compact circuit that detects voltage abnormalities effectively. Test results illustrated that the voltage of the safety hysteresis comparator for transient overvoltage detection in the track circuit in the normal occupancy state was 6.6 V. When the system failed, the voltage was higher than V_{hyst_H}, so V_o was in a high state. When the voltage was lower than V_{hyst_L}, the V_o was in a low state. In addition, the V_{hyst} difference was 4.4 V. The detected pulse added one more value to the digital counter circuit. Furthermore, the study revealed that installing transient overvoltage detection in the track circuit enabled the monitoring of voltage failure in the railway signaling system's track circuit. Additionally, it confirmed the hysteresis comparator function in safe mode. The circuit was designed to meet the safety failure mode requirements outlined in the IEC 61800-5-2 standard. This was done to ensure the system's stability and reliability and to improve the performance of the track circuit used for controlling the State Railway of Thailand's operations.

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