

Application of Electronic Load Circuit for Electrical Safety by using a Serial Mode Comparator

Abstract. This research presented an electronic load circuit for electrical safety by using a serial mode comparator as a protection device against surges caused by electrical power lacking stability and quality. The application of comparators in detecting overvoltage and driving electronic load is possible because of a transistor which is a simple device for failure prevention used in the circuit design. The properties of the circuit can be set. Relation management for failures which might occur in the electrical system is done through SPDs for surge protection. The electronic load is used as a device to reduce swell. The experiment showed that the electronic load circuit could work according to the design, without any failure, and was efficient. The let-through voltage which came to the load did not reach the level at which electrical devices and electronics would get the failure. The circuit could work without interruption. Moreover, the results from the Failure Modes and Effects Analysis (FMEA) showed that they met the specified standards.

Streszczenie. W pracy przedstawiono układ obciążenia obwodu elektrycznego/elektronicznego zabezpieczający obwód przed uszkodzeniem powodowanym przez brak stabilności zasilania. Układ wykorzystuje szeregowo połączenie komparatorów reagujących na przepięcia. Eksperymenty wykazały skuteczne działanie obwodu. Zastosowanie obwodu z szeregowo połączonymi komparatorami do zabezpieczania układów elektrycznych przed przepięciami.

Keywords: Electronic load, Comparators, Swell voltage, Failure modes and effects analysis (FMEA).

Słowa kluczowe: przepięcia, zabezpieczenia, komparatory.

Introduction

Development of a country requires modern technology to drive the growth of the nation in terms of economic value. The electricity and electronics industries have played a significant role in enabling such progress and creating innovations for other industries. There are many important parts of many products such as electrical devices, electrical power devices, automotive electronics, medical tools, smart agriculture, sensors, communication devices, and energy management systems. As the age of Industry 4.0 approaches, electrical devices have been used by people with greater frequency for their convenience. With artificial intelligence from electronics technology, many electrical devices have become smarter. Further, technology has also advanced, resulting in quicker speeds for their response. Changes in the electrical systems which supply technologies might lead to the problem of electricity quality in the future. A question might arise from the voltage, current and frequency rate from the normal state, as specified in IEEE Std. 1159 [1], which might be natural phenomena, electrical failure, device switching, incorrect grounding, or others [2], as shown in Fig. 1



Fig.1. Failure in an electronic device caused by the swell

These problems will not only cause failure in the electrical system and electrical devices in terms of quality, but also put users in danger. There are two types of issues regarding surge: 1) Overvoltage for a short period, which is caused by lightning. There are many prevention devices according to IEEE Std. C62.41, such as GDT and MOV. Although there are many protection devices, some electrical and electronic devices still experience failure, as shown in Fig. 1. This problem with swell has not been solved successfully in all cases 2) Failures in the electrical system in each region of Thailand are different. As such, they need to be analysed to improve the quality of electrical power based on actual events.

This paper presents a way to reduce the failures that occur in electrical and electronic devices which are connected to the electrical system and caused by the swell. The electronic load is used as a device to reduce such failure, while a comparator circuit is used to detect the level of swell for comparison with the reference level of swell. The comparator circuit contains a transistor [3-6]. To make a comparison, the window is designed to detect different levels of voltage [7]. It is connected in a serial mode [8,9] so that it can work for safety.

Relationships of Surge Protection Device

To manage the relationships of surge protection device (SPD) [10,11], it is essential to consider the relationships in terms of reception, limitation or absorption of energy in each device. That is, GDT at the first end must be able to suppress the power (V_{GDT}) caused by lightning to transfer to a MOV device next to the V_{MOV} to decrease the level so there is no failure in accordance with the IEEE Std C62.41 [12,13]. If the overvoltage cannot be suppressed or it decreases below the working condition, a swell protection device with electronic load can still reduce it so that the voltage V_{ELS} is at a safe level for electrical and electronic devices. The devices also work smoothly. The relationship management for the surge protection device can be shown in Fig. 2.

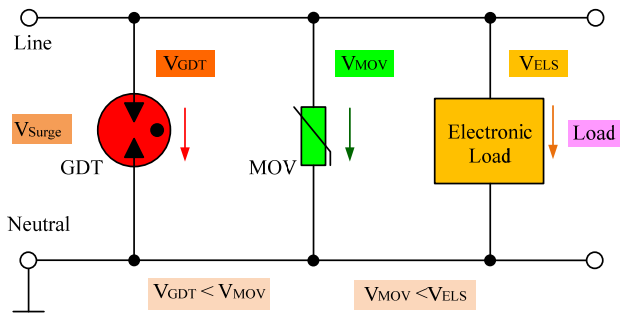


Fig. 2. Management of relationships for the surge protection device

The majority of electrical devices are designed to work with 230 VAC. If there is a failure in the electrical system, in this case, overvoltage ($230\text{VAC} \pm 10\%$) [14], the electrical device might malfunction or experience failure to the point that repair is not possible [15].

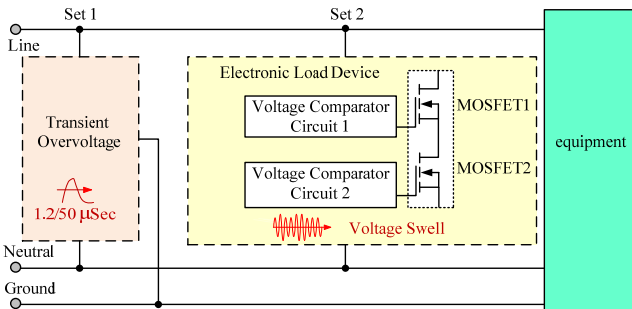


Fig. 3. Block diagram of the surge protection device

Fig. 3 shows the block diagram of the surge protection device for AC. Inside the surge protection device, there are two kinds of operation. First, the surge protection device consists of GDT and MOV devices with the fastest response time to control the let-through voltage so that it is manageable. Second, a swell suppressor consists of electronic load to control the clamping voltage to remain in the standard range.

Swell voltage comparator detector

A comparator has been designed with transistors to compare the voltages, as shown in Fig. 4.

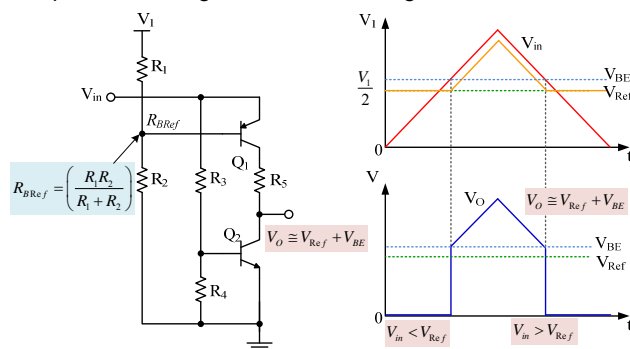


Fig. 4. Comparator circuit

A comparator circuit without feedback consists of 2 transistors [5-7]. Transistor Q_1 provides the comparator with the function of amplification for input signal, as shown in Equations (1) and (2).

$$(1) \quad I_{B_{Ref}} = \left(\frac{V_{in} - V_{BE(on)} - V_{Ref}}{R_{Ref}} \right)$$

$$(2) \quad R_{B_{Ref}} = R_1 // R_2 = \left(\frac{R_1 \times R_2}{R_1 + R_2} \right)$$

V_O is set so that the reference voltage can be used as V_{Ref} . The reference voltage is calculated from resistance R_1 and R_2 in the format of voltage divider circuit, as shown in Equation (3) with the clamping voltage at V_{BE} of Q_1 , as shown in Equation (4).

$$(3) \quad V_{Ref} = \left(\frac{R_2}{R_1 + R_2} \right) \times V_1$$

$$(4) \quad V_O \cong V_{Ref} + V_{BE}$$

To use a comparator with no feedback, a circuit can be added to increase the output signal so that the output signal can be logically set as 0 (off) or 1 (on). Transistors Q_4 will work as a switch to provide bias to the transistors to stay in a cut-off mode and the same status as an open circuit. The bias will then be supplied to the transistors to be in a saturation mode, the same status as a closed circuit, as shown in Equation (5). A large amount of current will pass through the transistors, and the output voltage will have the same value as 0, as shown in Equation (6).

$$(5) \quad V_{O(Cutoff)} = V_2 - (I_C \times R_7) = V_2 - 0 = V_2$$

$$(6) \quad V_{O(Sat)} = V_2 - (I_C \times R_7) = V_2 - V_2 = 0$$

When the voltage V_{in} is less than the reference voltage V_{Ref} , the output signal of the comparator will be 0V. When the voltage V_{in} is higher than the reference voltage V_{Ref} , the output voltage of the comparator will be similar to V_2 , as shown in Fig. 5

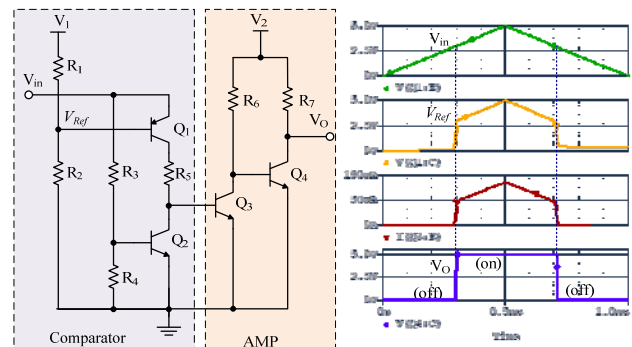


Fig. 5. Comparator with increased output signal

Block diagram of a comparator

The comparator circuit with increased output signal can be illustrated as a block diagram similar to op-amp, as shown in Fig. 6.

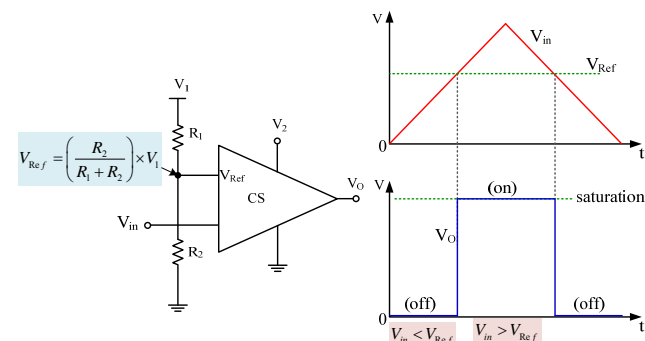


Fig. 6. Block diagram of a comparator

To design comparators, there is only one reference voltage. The output voltage is set to calculate resistance values R_1 and R_2 as voltage divider circuit. When $V_{in} < V_{Ref}$, the output voltage will be the same as the voltage put to V_2 . When $V_{in} > V_{Ref}$, the output voltage will be 0.

Two-level comparator circuit

In the two-level comparator circuit for electronic load in a serial mode, there must be comparator CS₁ and CS₂ to detect the voltage level. When the input voltage V_{in} is the same as the reference voltage V_{Ref1}, there will be output signal V_{O1} to make MOSFET₁ turn ON [16]. When the voltage V_{in} is higher and becomes the same as the reference voltage V_{Ref2}, the output signal V_{O2} of CS₂ will make MOSFET₂ turn ON, resulting in the current I_O passing through both MOSFETs in a serial mode. When the input voltage V_{in} decreases and becomes the same as the reference voltage V_{Ref2}, the output of the comparator CS₂ will be 0, making MOSFET₂ turn OFF. When the voltage V_{in} decreases and becomes the same as the reference voltage V_{Ref1}, the output of the comparator CS₁ will be 0, making MOSFET₁ turn OFF. When there is no electricity I_O, the electronic load stops working, as shown in Fig. 7. T₁ and T₂ are shown in Equation (7).

$$(7) \quad T_1, T_2 = V_{Ref2} - V_{Ref1}$$

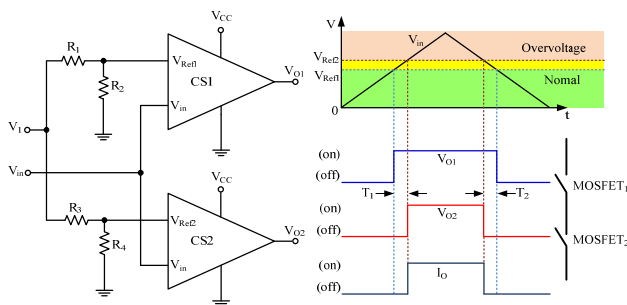


Fig. 7. Two-level comparator circuit

The principle of the surge protection device

The electronic load circuit to reduce swell voltage in the low voltage electrical system has been designed with the voltage RMS, which is higher than the standard level (namely 230V ± 10%). The circuit has been designed in parallel without considering the electrical load current. When there is overvoltage in the system, comparators CS₁ and CS₂ will detect the voltage level to drive the electronic load in a serial mode [9], as shown in Fig. 8.

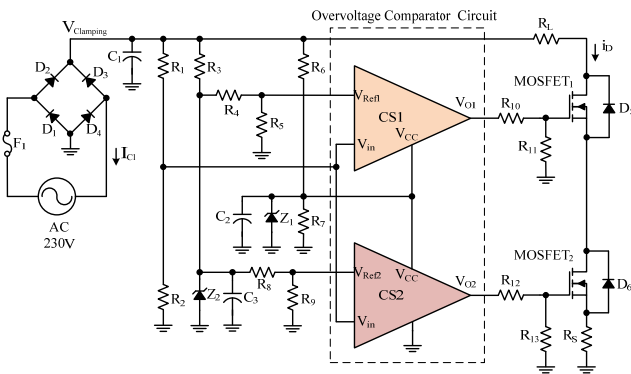


Fig. 8. Electronic load alongside comparator

When voltage V_{in} reaches the specified level, as shown in Equation (5), there will be output signals V_{O1} and V_{O2} in order to drive the electronic load by overvoltage in the system. The electronic load circuit will take the current (Leakage Current :I_{Cl}) and control the clamping voltage (Clamping Voltage :V_C or V_C) to be in a suitable range, as shown in Equations (6) and (7). MOSFET will act as a receptor of overvoltage as another load in the system, as shown in Equations (8)-(12) [15-16].

$$(8) \quad V_{in} = \frac{V_{ac} \sqrt{2} \times R_2}{(R_1 + R_2)}$$

$$(9) \quad V_C = V_{M1} + V_{M2} + i_D (R_L + R_S)$$

$$(10) \quad V_C = V_{RL} + V_{M1} + V_{M2} + V_{RS}$$

$$(11) \quad I_{Cl} \cong i_D = \frac{V_C}{R_{EL}} = \frac{V_C}{R_L + R_{M1} + R_{M2} + R_S}$$

$$(12) \quad P_{EL} = V_{C(t)} \times I_{Cl(t)}$$

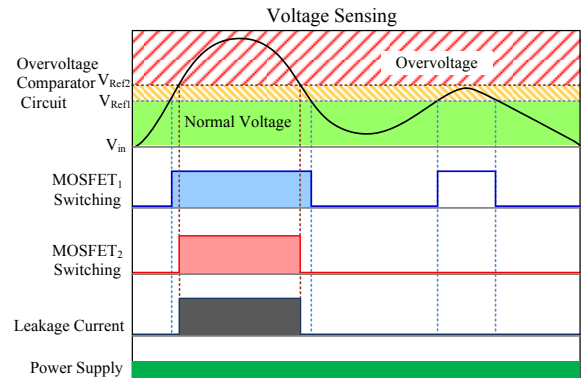


Fig. 9. Signals of electronic load circuit with a comparator

According to Fig. 9, the electronic load circuit alongside a comparator to detect swell has been set regarding the reference voltage for V_{Ref1} and V_{Ref2}. When there is overvoltage, comparator CS₁ will make MOSFET₁ turn ON. When there is overvoltage remaining, comparator WCS₂ will turn ON, resulting in leakage current passing through MOSFET₂ for the entire circuit. Overvoltage will be reduced in the form of electrical waves, as shown in Fig. 10.

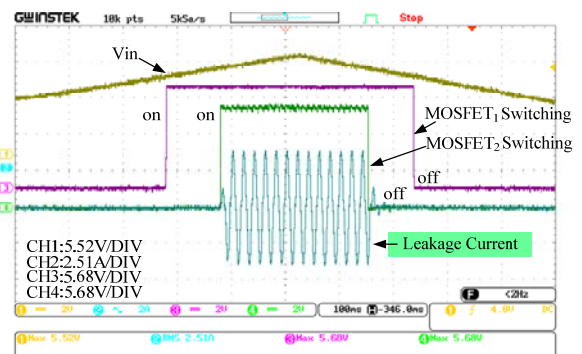


Fig. 10. Waves of the comparator and electrical current passing through the electronic load

The electronic load circuit has been designed for safety by using comparators in a serial mode. The failure and possible effects have been analysed with the comparator circuit in accordance with the safety principles to ensure that the electronic load circuit with comparators works reliably without any critical failures. There were two sets of devices for testing: a surge protection device and a swell suppressor.

Safety analysis of comparator

To analyse the type of failure and possible effects, the method called Failure Modes and Effects Analysis (or FMEA) [17] has been used to identify the failure in safety of the electronic load circuit in order to prevent collapse. The analytical principle has been set in IEC 61496-1 [18]. The results of the analysis can confirm that when there is a failure in the electronic load, the system will show Fail-Safe status [19]. Further, the system must not cause any failure, as shown in Table 1.

Table 1. FMEA of the developed comparator

Devices	Failure mode	effect of the comparator	Effect of failure	effect of Load Electronic
R ₁	Open circuit	Change of circuit characteristic	c	Δ
	Short circuit	No Output Signal	b	Δ
	R ₁ * 2	Change of circuit characteristic	c	Δ
	R ₁ * 0.5	Change of circuit characteristic	d	Δ
R ₂	Open circuit	No Output Signal	b	Δ
	Short circuit	No Output Signal	b	Δ
	R ₂ * 2	Change of circuit characteristic	d	Δ
	R ₂ * 0.5	Change of circuit characteristic	c	Δ
Q ₂	Open circuit	Normal circuit	f	Δ
	Short circuit	No Output Signal	b	Δ

Note (*0.5) and (*2) refer to the standard values
 (a) : Normal Output (b) : No Output
 (c) : window Voltage reduced (d) : window Voltage increase
 (e) : Output as V₂ (f) : Half reduction output
 Δ : no significant consequences of Electronic load
 ▲ : significant consequences of Electronic load

Test results of the surge protection device

The circuit has been set up to test SPD_s GDT and MOV. Test waves have been added in accordance with the standards IEEE [12,13] and IEC [20] (1.2/50μS) at 6,000V and the oscilloscope has been used to measure the let-through voltage (Vlt) at the output. The results were recorded in Table 2.

Table 2. Test results for the surge protection device

Sequence Test	Let Through Voltage (Vlt)	
	GDT (V)	MOV (V)
1	815.2	496.5
2	852.7	509.0
3	837.5	510.2
4	857.8	526.6
5	809.0	540.3
6	837.5	554.0
7	807.8	557.9
8	837.5	564.1
9	826.6	568.7
10	834.0	570.4

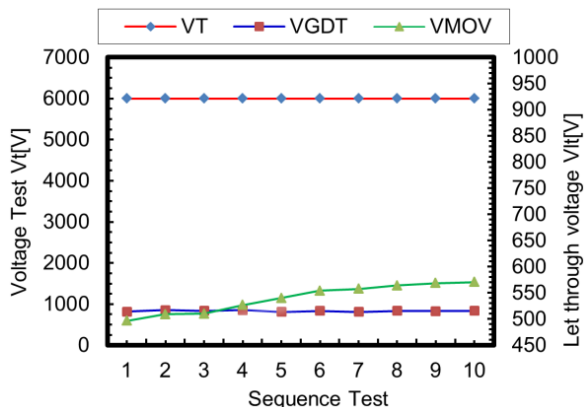


Fig. 11. Graphic of the relationship between voltage test and let-through voltage through GDT and MOV

According to Fig. 11, there is a relationship between the voltage test at 6,000V and let-through voltage through surge protection devices GDT and MOV. The output signal waves for the surge protection devices GDT and MOV are shown in Figs. 12 and 13.

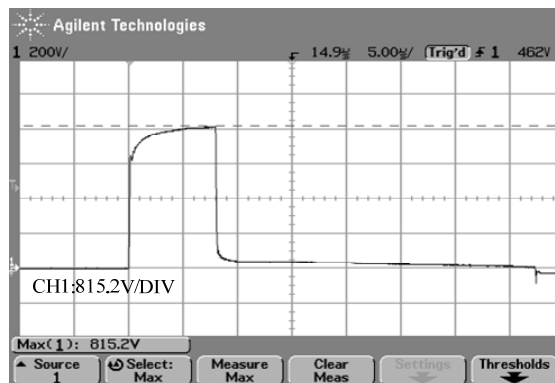


Fig. 12. Output signal waves for the surge protection device GDT at 6,000V

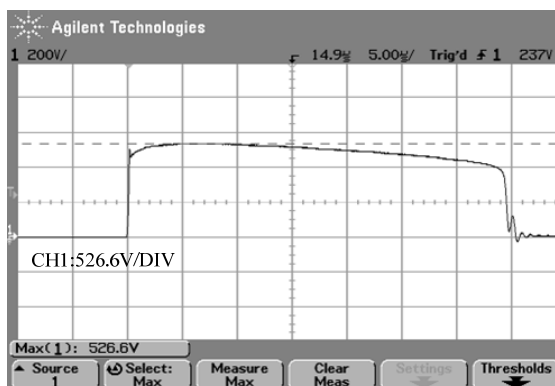


Fig. 13. Output signal waves for the surge protection device MOV at 6,000V

Test results from the swell suppressor

To test the swell suppressor, the electronic load has been added to suppress the swell, as shown in Fig. 14. The swell waves are shown in Fig. 15.

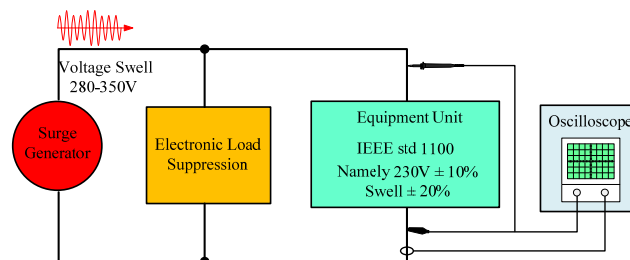


Fig. 14. Circuit to test the electronic load in the swell suppressor

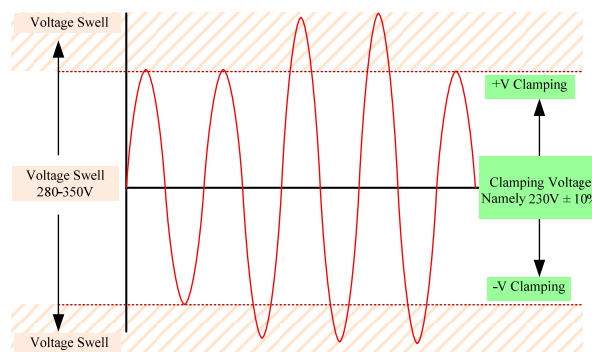


Fig. 15. Swell waves

After the setup, AC voltage was added with 280V-350V at 50 Hz. The overvoltage test waves are shown in Fig. 16, and the oscilloscope has been used to measure the electrical current and clamping voltage at the output. The data was recorded in Table 3.

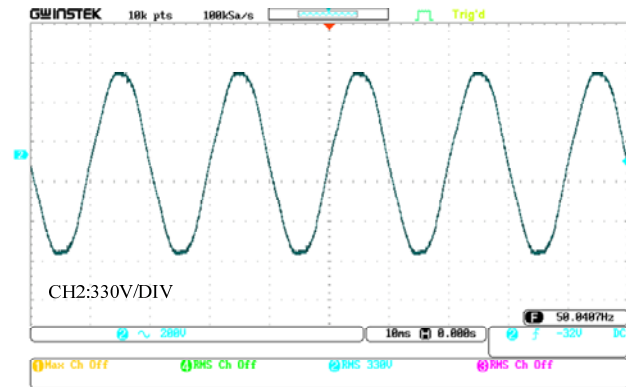


Fig. 16. Test waves at 330V

Table 3. Test results for the electronic load in the swell suppressor

Sequence Test	Voltage test Vt[V]	Clamping voltage Vc[V]	Leakage current CI[A]
1	280	202.98	2.58
2	290	206.76	3.21
3	300	212.56	3.38
4	310	217.47	3.50
5	320	221.25	3.71
6	330	227.53	3.96
7	340	232.18	4.60
8	350	234.09	5.17

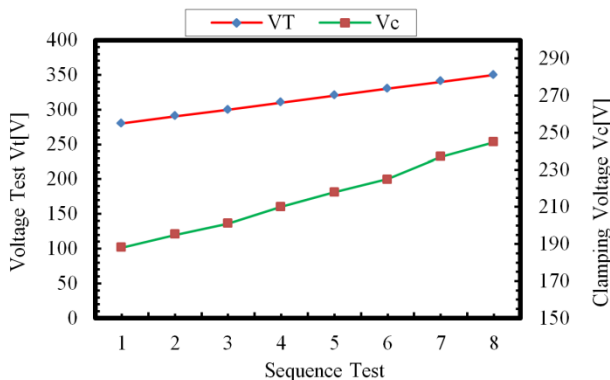


Fig. 17. Graphic relationship between voltage test and clamping test

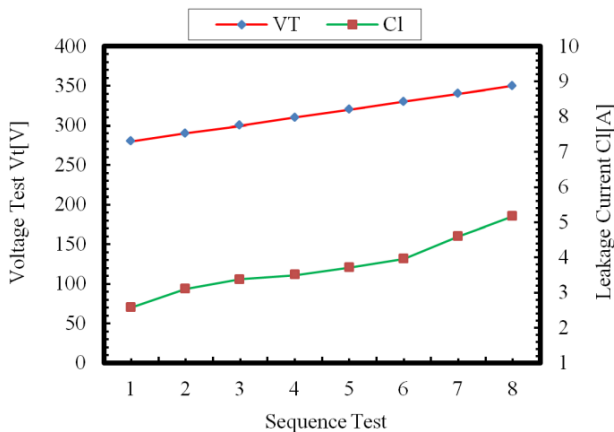


Fig. 18. Graphic relationship between voltage test and clamping test

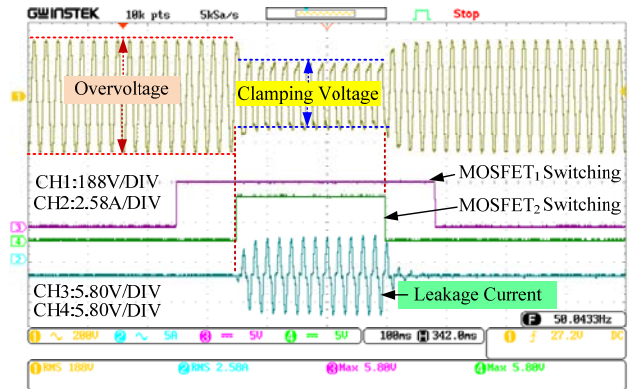


Fig. 19. Output signal waves for the electronic load in the swell suppressor

According to Fig. 19, the signal waves of the electronic load and the let-through voltage at the output of the electronic load are shown. CH1 is the swell waves, the comparator works at CH3. CH4 is the wave for electronic load in the let-through voltage at CH2. When the signal waves are magnified, there is delay time to detect any failure caused by the overvoltage, resulting in the safety of the electronic load, as shown in Fig. 20.

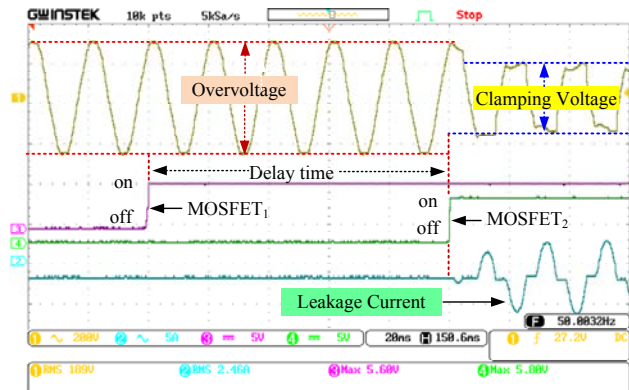


Fig. 20. Output signal waves of the electronic load and comparator

Conclusion

This research paper presents an electronic load circuit for safety by using comparators in a serial mode as a surge protection device for a low-voltage electrical system. When the quality of the electrical system is inadequate, it might cause failures in electrical and electrical appliances. The design has been organised to consider the potential failures to electrical and electronic devices by managing the relationships between surge protection devices (SPDs) to suppress overvoltage in the magnetic field caused by lightning. To design the electronic load circuit, comparators were used to detect overvoltage. Transistors were used in the design of the comparators and devices were used by the principle alongside the analysis from the computer software as well as the actual devices. The results in the previous section show that they accord to the design. The developed electronic load can accurately work out a fail-safe status. The test results from the Failure Modes and Effects Analysis (FMEA) were according to the standards IEC 61496-1. In this paper, there were 2 types of surge protection devices assessed, with the results as follows: 1) Test results from the surge protection devices were in accordance with the designed experiment and as expected. The surge protection devices could suppress overvoltage from the magnetic field caused by lightning when signal

waves complying with the IEEE C62.41 at 6,000V (1.2/50 μ S) were used. The let-through voltage was low and acceptable. 2) Test results from the swell suppressor followed the designed experiment and were as expected. The electronic load could suppress overvoltage when it was over the standards, resulting in the clamping voltage to remain at an acceptable level.

Authors: Mr. saktanong wongcharoen, E-mail: saktanong.w@gmail.com; Dr. Sansak Deeon, E-mail: sdeeon2013@gmail.com. Department of Electrical Engineering, Pathumwan Institute of Technology, 833 Rama1 Wangmai District, Bangkok, Thailand; Dr. Narong Mungkung, E-mail: narong.kmutt@yahoo.com Department of Electrical Technology Education, King Mongkut's University of Technology Thonburi, 126 Pracha Uthit Rd., Bang Mod, Thung Khru, Bangkok, Thailand.

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