engineering proceedings

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Proceeding Paper

Enhanced Safety Logic Solver Utilizing 2oo3 Architecture with Memristor Integration †

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† Presented at the 10th International Electronic Conference on Sensors and Applications (ECSA-10), 15–30 November 2023; Available online: https://ecsa-10.sciforum.net/.

Abstract: A safety instrument function (SIF) averts hazardous incidents that may arise due to diverse anomalies within a system. The SIF prevents potential dangers by comprising three integral components—the sensing element, the logic solver, and the final element. The 2oo3 architecture is the optimal configuration for each SIF component, employing both AND and OR logic designs for its voting mechanism. Type A devices, recognized for their passive nature, exemplify robustness and reliability. While these devices are acknowledged as the most dependable, semi-conductor devices or microcontrollers, categorized as Type B, often find application in logic processing. This paper introduces the incorporation of memristors, which are inherently passive devices with memory attributes, into the system. The logic solver, which calculates confidence values, exhibited greater efficacy than Type B devices. Verification was conducted via LTspice circuit simulations. The results of the memristor for Logic Solver in the safety instrumentation function (SIF) IEC 61508/61511 standard are as follows: The voter circuit has the lowest components and failure rate and highest mean time to failure. This is more reliable than the other voter.

Keywords: memristor; 2oo3; logic solver; fail-safe

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Citation: Summatta, C.; Sonasang, S. Enhanced Safety Logic Solver Utilizing 2oo3 Architecture with Memristor Integration. *Eng. Proc.* **2023**, *58*, 37. https://doi.org/10.3390/ecsa-10-16006

Academic Editor: Jean-marc Laheurte

Published: 15 November 2023

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1. Introduction

The enhanced safety logic solver holds a pivotal role in fail-safe systems, and it is primarily responsible for meticulously processing the monitoring of sensor unit failures within a given system [1–4]. It is the linchpin of safety mechanisms dedicated to averting potential hazards that may ensue from diverse anomalies that can occur for various reasons. Such hazards are especially critical in railway signaling, elevator door mechanisms, and electric motor drive systems. The safety evaluation of the 2oo3 voting logic solver is paramount in achieving a stringent safety level of SIL3. This intricate process involves receiving signals from three Type A sensors and meticulous processing via a static voting component. Subsequently, the signals are directed toward the logic solver and window comparator circuits [5,6], culminating in transmitting a DC signal to the final element. The components within this subsystem encompass both Type A and Type B devices. Type A devices are characterized by their fundamental components, such as resistors, inductors, and capacitors, each with clearly defined failure modes. They consistently operate reliably even under predefined fault conditions, and their data integrity remains intact despite failure. In stark contrast, Type B devices incorporate integrated circuit components or microprocessors, which, while versatile, are less reliable, possess shorter lifespans, and are inherently less verifiable. As a groundbreaking addition to the field, memristors represent a novel category of passive devices [7] and are now recognized as the fourth fundamental electrical element. They exhibit behavior akin to resistors regarding ohmic characteristics while boasting intrinsic memory attributes [7–9]. Memristors have found extensive applications in various circuit domains, including digital circuits [10–14].

In the following sections, this paper presents the design and development of a two-out-of-three voter system that expertly incorporates memristors. These innovative components are harnessed to craft a robust logic circuit that is specifically tailored for deployment within the Safety Instrument Function Level 3 (SIL3) system [15,16]. Performance analysis is carried out via the meticulous examination of the mean time of failure (MTTF) [17], with rigorous testing facilitated by the LTspice simulation program [18].

2. Fundamental Theory and Method

2.1. Safety Instrumentation Function

The safety instrumentation function (SIF), as shown in Figure 1, guided by IEC 61508/61511 standards [15], safeguards operational systems from accidents caused by anomalies. It comprises three key elements. The sensing element converts process variables into standardized electrical signals for monitoring and the control system display. The logic solver processes signals, compares them to set values, and delivers them to the end device. It includes a power supply, central processing, communication, and control components. The final element converts processed signals into a format that is suitable for the system controller, and it is vital for safety considerations. The IEC standards assign a safety integrity level (SIL), ensuring that equipment design aligns with acceptable error levels considering cumulative component failure hazards.

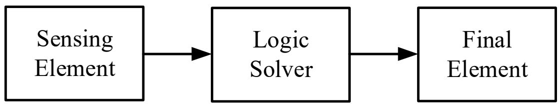

Figure 1. Safety instrumentation function (SIF) [15].

2.2. The 2oo3 Voting

The 2oo3 voting consists of six switches that detect errors in 2 out of 3 detectors, and the logic design has three AND logics and OR logics following Equation (1).

$$Y = AB + BC + CA \tag{1}$$

From past research [1–3], the 2oo3 detection method is very safe. It is a dynamic processing model. Static processing is a process without a contact, like a dynamic one, but uses a static switch instead. The use of the equation from the same logic equation is shown in Figure 2.

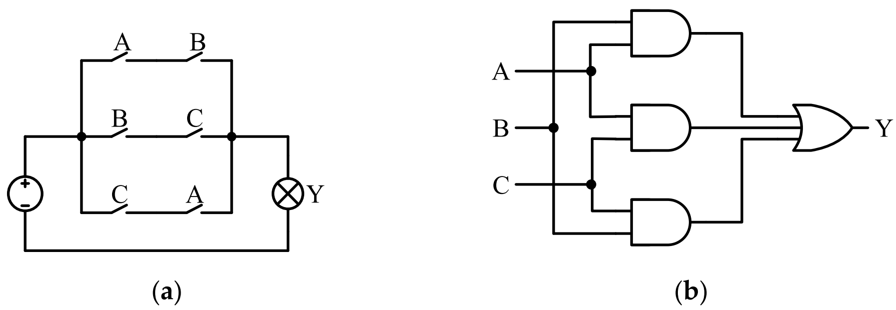

Figure 2. The 2oo3 voting: (**a**) relay circuits; (**b**) logic circuits.

2.3. The Memristor

A memristor is a bipolar passive element with a relationship between charge and flux [7]. A memristor is a combination of the term memory and resistor. Ideally, the resistance of the memristor increases if the charge flows through the memristor in one direction, and it decreases if the current flows in the other direction. When the current stops flowing, the resistance of the memristor remains constant [7–9]. The symbol and current–voltage characteristic curve are shown in Figure 3.

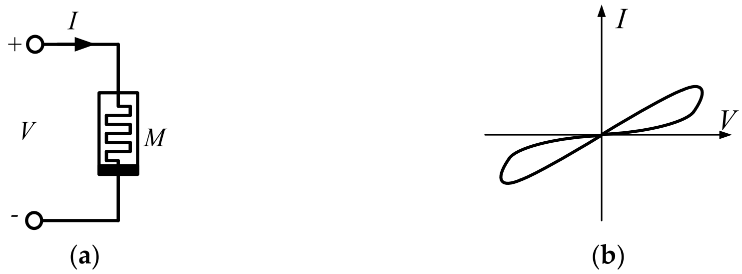

Figure 3. Memristor [7]: (**a**) symbol; (**b**) *I-V* characteristic curve.

The characteristics of the memristor can result in a voltage divider circuit, as presented in [10–14], and the circuit can create OR logic and AND logic gate circuits, as shown in Figure 4.

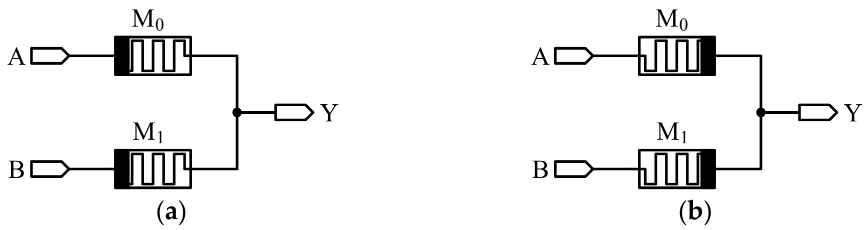

Figure 4. Logical OR and AND with memristor [8,9]: (**a**) logical OR; (**b**) logical AND.

The ideal use of a memristor as a logic circuit is a passive circuit that does not require a power supply, utilizing a logic output signal generated by a voltage divider from the memristor. Moreover, gates and OR gates behave differently due to the property of the memristor in terms of the current flow direction. Input side logic 1 is the supply voltage, and logic 0 is the ground. The output side receives logic 0 or 1 from the voltage provided by the memristor's voltage divider. The operation of AND logic with a memristor is shown in Figure 5.

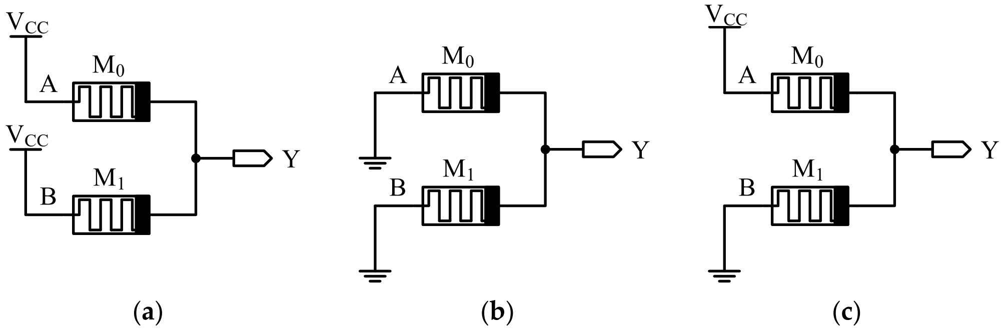

Figure 5. Logical AND with memristor [10,11]: (**a**) $M_0 = M_1 = R_{off}(\text{Y} = \text{V}_{CC})$; (**b**) $M_0 = M_1 = R_{on}(\text{Y} = \text{GND})$; (**c**) $M_0 = R_{off}, M_1 = R_{on}(\text{Y} = logic\text{“}0\text{”})$.

Figure 5a shows that input A is logic 1 and input B is logic 1; no current flows through the circuit, and the output is logic 1 or V_{CC}. Figure 5b shows that input A is logic 0 and B is logic 0; there is no current flow through the circuit, and the output is logic 0 or GND. Figure 5c shows that input A is logic 1, and B is logic 0, the resistance of memristor M_0 increases (R_{off}), the resistance of Memristor M_1 decreases (R_{on}), the current can flow from V_{CC} to GND, and the output is logic 0.

Figure 6a shows that input A is logic 1, and input B is logic 1. The current can flow through the circuit, and the output is logic 1 or V_{CC}. Figure 6b shows that input A is logic 0 and B is logic 0; there is no current flow through the circuit, and the output is logic 0 or GND. Figure 6c shows that input A is logic 1, and B is logic 0. The resistance of memristor M_0

decreases (R_{on}), the resistance of memristor M_1 increases (R_{off}), the current can flow from V_{CC} to node Y, and the output is logic 1.

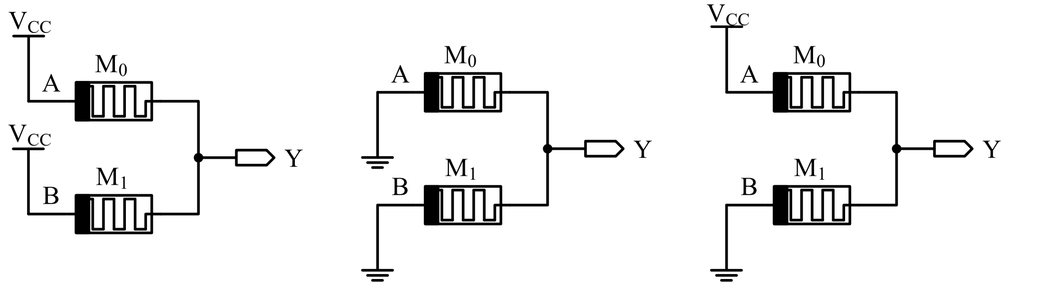

Figure 6. Logical OR with memristor [10,11]: (**a**) $M_0 = M_1 = R_{on}(\mathrm{Y} = \mathrm{V}_{CC})$; (**b**) $M_0 = M_1 = R_{off}(\mathrm{Y} = \mathrm{GND})$; (**c**) $M_0 = R_{on}, M_1 = R_{off}(\mathrm{Y} = logic\text{“}1\text{”})$.

3. Results and Discussion

3.1. 2oo3 Logic Solver with Memristor

Based on the theories and methods mentioned above, a 2oo3 logic solver with a memristor circuit can be designed, as shown in Figure 7.

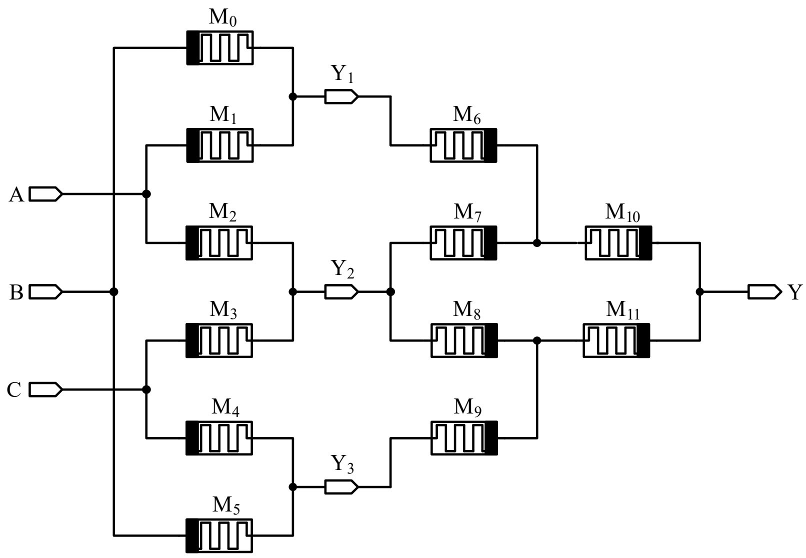

Figure 7. The 2oo3 logic solver with memristor.

Figure 7 shows memristors M_0 to M_5 instead of three two-input AND gates, and it shows M_6 to M_{11} instead of the three-input OR gate. The operation of the circuit was tested with the simulation program LTspice. The results are obtained according to the truth table of 2oo3, as shown in Table 1.

Table 1. The truth table of 2oo3 voting.

A	B	C	Y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

3.2. Reliability Value

The military handbook "Reliability Prediction of Electronic Equipment" (MIL-HDBK-217F) [18] proposed a failure rate for electronic equipment. This work compares 2oo3 voters in different logic IC and memristor devices (in this case, the memristor is replaced with a resistor), as shown in Table 2.

Table 2. The failure of electronic equipment.

No.	Notation	Components	Failure Rate (10^{-6} h)
1	λ_P	Opto-coupler [2]	0.08160
2	λ_D	Diode [2]	0.01213056
3	λ_P	Logic ICs	0.15
4	λ_P	Resistor	0.0069

The failure rate of electronic 2oo3 voter devices can be calculated via the sum of the failure rate, comparing the two devices using the same model: the Chip Carrier (Surface Mount) Package Type Correction Factor. The overall failure rate, the decrease in the number of devices with respect to a lower failure rate, and the mean time of failure [17] are the approximations of reliability with respect to the failure rate. If the failure rate is lower, the average time to failure increases, as shown in Table 3.

Table 3. Comparison of the sum of failure rate and mean time to failure.

Type of 2oo3 Voter Devices	The Sum of Failure Rate (Hour)	The Mean Time to Failure (Hour)
Opto-coupler [2]	0.4896×10^{-6}	2,042,483
Opto-coupler and Diode [2]	0.3385×10^{-6}	2,953,947
Logic ICs	0.6000×10^{-6}	1,666,666
Memristor	0.0414×10^{-6}	24,154,589

Table 3 shows a comparison of the sum of the failure rate and the mean time to failure, showing that the memristor has the lowest failure rate and the highest mean time to failure. Four logic gates and six memristors are used to calculate the sum of the failure rate of logic ICs. The proposed 2oo3 with the memristor has a reliability value that is 14.49 times that of the logic IC model.

4. Conclusions

This paper introduces a novel 2oo3 voter integrated with a memristor for the Enhanced Safety Logic Solver in the safety instrumentation function (SIF) following the IEC 61508/61511 standard. The objective of this study is to showcase an alternative application of memristors. Notably, the proposed voter circuit for the Enhanced Safety Logic Solver exhibits several advantages, including reduced component count, lower failure rates, and superior mean time to failure. These attributes collectively render it a more reliable choice compared to conventional alternatives.

Author Contributions: Conceptualization, C.S.; methodology, C.S. and S.S.; software, C.S. and S.S.; validation, S.S., formal analysis, C.S.; investigation, C.S. and S.S.; writing—original draft preparation, C.S.; writing—review and editing, S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to demonstrate gratitude toward the Department of Electronic Technology, Faculty of Industrial Technology of the Nakhon Phanom University, for providing research time, the research grant, instrumentation, and financial support.

Conflicts of Interest: The authors declare no conflict of interest.

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