The 13th Industrial Electronics Seminar 2011 (IES 2011)
Electronic Engineering Polytechnic Institute of Surabaya (EEPIS), Indonesia, October 26, 2011

Fault Tolerant Air Bubble Sensor using Triple Modular Redundancy Method

Noor Cholis Basjaruddin[1,2], Kuspriyanto[1], Yoga Priyana[1]
[1]School of Electrical Engineering and Informatics, Bandung Institute of Technology
Jl. Ganesha no. 10, Bandung, Indonesia
[2]Department of Electrical Engineering, Politeknik Negeri Bandung
Jl. Gegerkalong Hilir, Ds.Ciwaruga Kotak Pos 1234 Bandung 40012, Phone: +62-22-2013789
ppmteam@gmail.com

Abstract

Detection of air bubbles in the blood is important for various medical treatments that use Extracorporeal Blood Circuits (ECBC), such as hemodialysis, hemofiltration and cardio-pulmonary bypass. Therefore a reliable air bubble detector is needed. In this study designed a fault tolerant air bubble detector. Triple Modular Redundancy (TMR) method is used on the sensor section. A voter circuit of the TMR will choose one of three sensor output to be processed further. Application of TMR will prevent errors in the detection of air bubbles, especially if the sensor fails to work.

Keywords: *air bubble detector, triple modular redundancy, extracorporeal blood circuits*

1. Introduction

The rapid development of technology in the all area, including to the technology used in a variety of medical treatment. Equipment used in hemodialysis, hemofiltration or cardio-pulmonary bypass requires the detection of air bubbles in the blood. The presence of air bubbles in the blood can cause local reactions such as tissue ischemia or necroses which sometimes can be fatal for the patient.

Air bubbles contained in the extracorporeal generally appear during the installation of the appliance. In addition, air bubbles can be formed by a blood pump, blood flow turbulence in the tubing and at the vascular access, as well as differences in temperature.

Micro air bubbles are currently recognized as a medical hazard in cardiac surgery. The entry of micro air bubbles into the venous or arterial system can be fatal. Venous emboli may lead to cardiovascular collapse or to paradoxical arterial emboli. Arterial emboli may occlude end arteries throughout the body and may cause serious diseases or death if they occlude cardiac or cerebral vessels.

Air bubble detection techniques can use infrared sensors, ultrasonic sensors or capacitor sensors. In addition to detection of air bubbles, the air bubble trapper is also developed.

2. Research Method

2.1 Capacitive Air Bubble Sensor

Characteristics of capasitive sensor from other research is shown in Table 1.

Table 1. Measured capacitance and voltage for different air bubble diameters[1]

Capacitance (nF)	Air Bubbles Diameter (mm)	Output Voltage (mV)
43.50	0	18.60
42.63	0.82	20.3
42.54	1.00	22.01
41.07	2.97	40.50
40.44	3.55	43.70
39.38	4.00	47.90

2.2 Triple Modular Redundancy (TMR)

Triple Modular Reduncandy (TMR) is a fault tolerant method using three modules that work together and get the same input signal.Output of TMR is one of the three output chosen with voting techniques. Block diagram of TMR is shown in Figure 1.

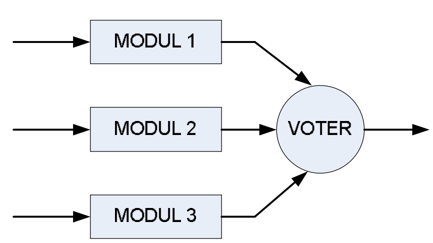


Figure 1. Triple Modular Redundancy.

2.3 Redundant Sensor Using TMR

Redundant sensors to improve the system reliability can be realized by various methods. The simplest method is to use two sensors, one primary sensor and a backup sensor. Redundant complex sensors can be realized by using many sensors in a matrix (sensor array). In this study redundant sensor using TMR is developed. Block diagram of the system being developed can be seen in Figure 2.

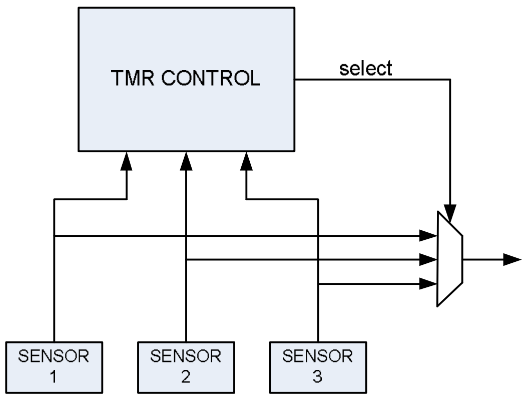


Figure 2. Redundant sensor using TMR method

2.4 Sensor Installation

Use of TMR on redundant sensor require the three sensors that are ideally equal and installed such that the three sensors measure the same magnitude in the same time. Example installation of sensors that meet these conditions can be seen in Figure 3. The figure show three capacitive sensors are mounted around the tube to measure air bubbles.

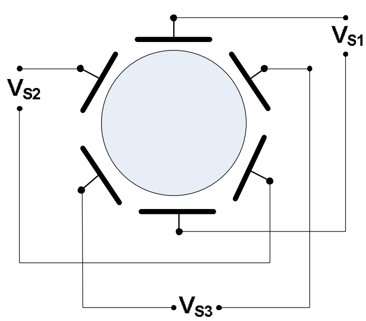


Figure 3. Installation of three capasitive sensors

2.5 Voting Technique

Determination of the redundant sensor output of three sensor output is called as the voting. Voting techniques commonly used in TMR are majority vote, mid-value vote, and the mean value vote. In the majority vote, output is selected from at least two same sensor output. In the other word that if a sensor is fail or not functioning properly, the sensor output is selected based on two other sensor output. In the mid-value voting techniques, the selected sensor output is the sensor output whose value is the middle value (median) of the three sensor output values. The selected sensor output can also be based on the average value of all sensor outputs, this technique is known as the mean value technique.

The mid-value voting technique is selected in this research. The consideration of this technique is easily implemented in the analog circuit.

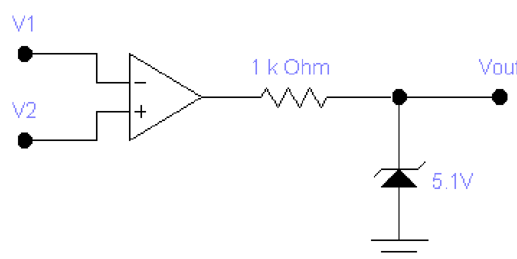
2.6 Mid value determination

Determination of the mid value of three sensor output done in hardware with analog components. The use of analog components can save the cost of implementation because the sensor output generally use analog signals. In addition, the use of analog components can reduce the error is caused by the digitalization process in digital circuit.

The electronic circuit to determine the mid value divided into two main sections. The first section is the comparator and the second is a multiplexer.

Comparator Section

Three voltage comparator circuits with the op-amp as main components are used in this section. Figure 4 shows a voltage comparator circuit. Figure 5 shows the block diagram of comparator section.



V1 < V2, Vout = 1
V1 > V2, Vout = 0

Figure 4. Voltage comparator circuit

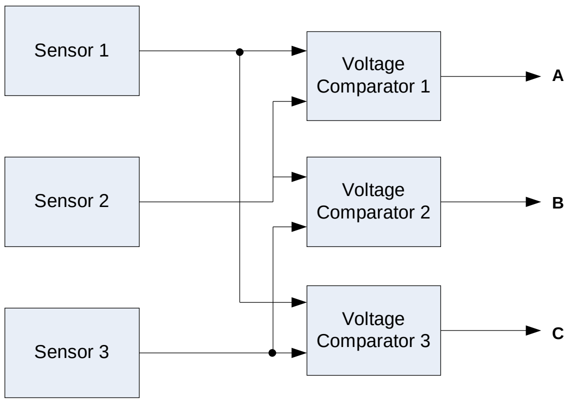


Figure 5. Block diagram of comparator

In Figure 5, A, B, and C are result of the comparisons between the output of sensors 1 and 2, 2 and 3, and 1 and 3. A, B, and C for various conditions is shown in Table 2.

Table 2. Output of comparator section.

Inputs	A	B	C
$V_{S1} < V_{S2}$	0	-	-
$V_{S1} > V_{S2}$	1	-	-
$V_{S2} < V_{S3}$	-	0	-
$V_{S2} > V_{S3}$	-	1	-
$V_{S1} < V_{S3}$	-	-	0
$V_{S1} > V_{S3}$	-	-	1

Based on Table 2, the redundant sensor output can be determined from the mid value. For example if A = 0, B = 0, and C = 0, meaning $V_{S1} < V_{S2}$, $V_{S2} < V_{S3}$, dan$V_{S1} < V_{S3}$. Figure 6 shows an illustration of this condition.

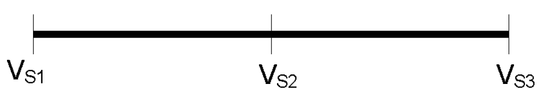


Figure 6. Mid value of sensor output

V_{S2} is the mid value of three sensor outputs. Table 3 shows the results of the sensor output selection by using the mid value voting.

Multiplexer Section

This section serves to process the output of comparator section to be used to determine the selected sensor output in hardware. Multiplexer designed by referring to Table 4 which is a truth table result of the development of Table 3.

Table 3. Sensor selection.

A	B	C	Sensor Selected
0	0	0	S2
0	0	1	none
0	1	0	S3
0	1	1	S1
1	0	0	S1
1	0	1	S3
1	1	0	none
1	1	1	S2

Table 4. Truth table of multiplexer.

A	B	C	SM1	SM2	SM3
0	0	0	0	1	0
0	0	1	-	-	-
0	1	0	0	0	1
0	1	1	1	0	0
1	0	0	1	0	0
1	0	1	0	0	1
1	1	0	-	-	-
1	1	1	0	1	0

A value of 1 in columns SM1, SM2, SM3 means output sensor of S1, S2, or S3 was selected as the mid value.

Based on Table 4 can be made a multiplexer with 3 inputs and 3 outputs. Three outputs of this multiplexer can be used to control the selector circuit. Figure 7 shows the block diagram of a multiplexer.

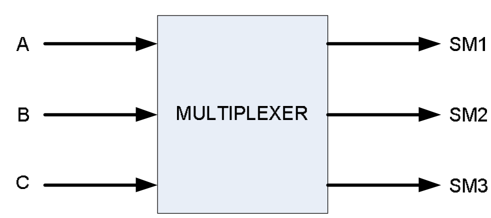


Figure 7. 3-to-3 multiplexer

2.7 Voter circuit (selector circuit)

The voter circuit composed of three transistors that function as switches. Figure 8 (a) shows the block diagram of voter and Figure 8 (b) shows the transistor as a switch that can be operated by providing logic zero or one on the input. If logic 1 is given at the input, the transistor will be on, and output of a sensor will be selected for further processing.

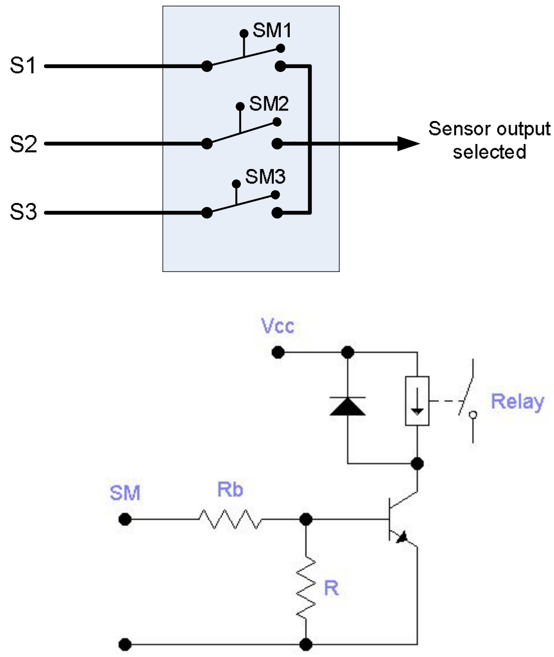


Figure 8. Block diagram of voter (a) Transistor As Switch (b)

3. Results and Discussion

3.1 Simulation of mid value determination

Figure 9 shows result of mid value determination simulation.

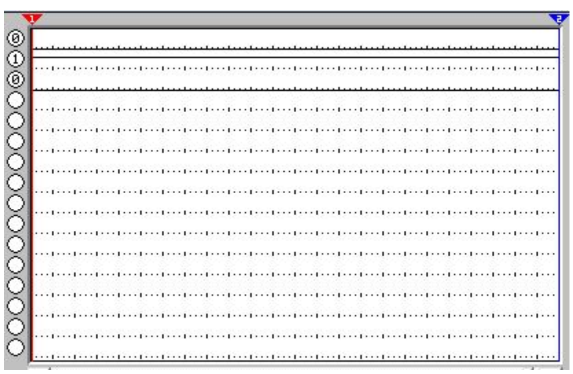


Figure 9. Result of mid value determination simulation.

This simulation shows that the determination of the mid value can be done by using 3 voltage comparators. In this simulation sensor 3 (S3) is selected.

3.2 Multiplexer simulation.

Figure 10 shows one of the simulation results with the input multiplexer 101 and output 001 (sensor 3 selected). Multiplexer in this simulation using three NOT gates, six AND gates and three OR gates.

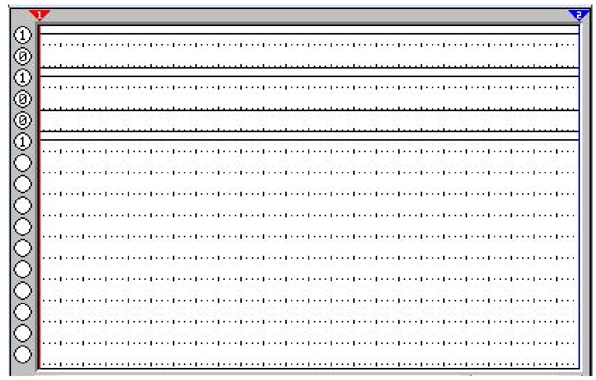


Figure 10. Simulation multiplexer.

3.3 Simulation of voter circuit.

Figure 11 shows the results of voter circuit simulation. At the beginning of this simulation, the redundant sensor output is the output of sensor 2. Sensor output which selected is the mid value of the entire sensor outputs. At the sec to sixth, sensor 2 (S2) output increased and greater than sensor 1 (S1) output. Now, sensor 1 output become mid value and selected as redundant sensor output. This simulation shows that the voter circuit can function properly.

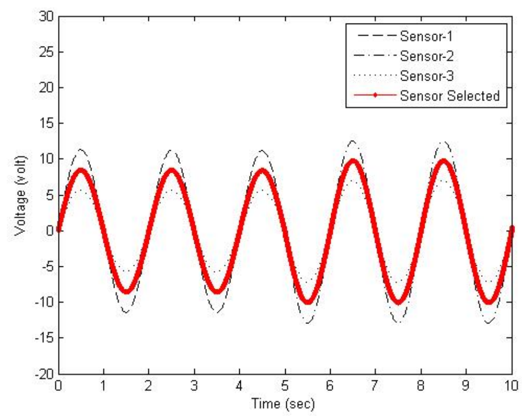


Figure 11. Result of voter circuit simulation

3.4 Simulation of Sensor Failure

In this simulation the sensor 2 (S2) damage experience. In Figure 12 it can be seen that at about 4.6 sec, sensor 2 fail of work, consequently voter must choose another sensor output. In this case sensor 1

(S1) is selected. This simulation shows that the reliability of systems using redundant sensors is higher than without the use of redundant sensors.

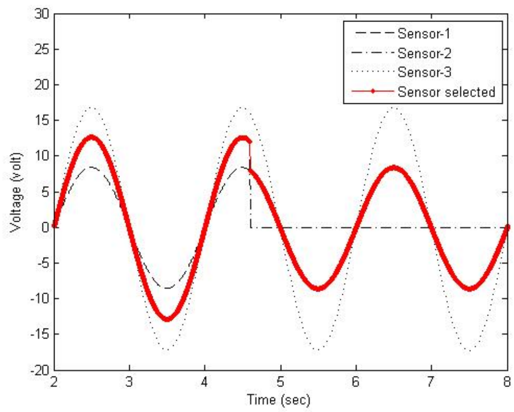


Figure 12. Simulation circuit voters.

For the purpose of observation on the simulation 3.3 and 3.4 the output of three sensors intentionally set has a pretty big difference. Simulations is done with the help of software Electronics Workbench (EWB) and the results are then processed with Matlab software.

3.5 System Reliability

Use of TMR on redundant sensors will increase system reliability. Failure in this system occurs when two or more sensors damaged. When only one sensor fails to work then the system can still work. Reliability of redundant sensors can be compared with the reliability of a sensor with a assumption that the voter circuit no damage.If the reliability of one sensor is RN and the reliability of redundant sensors is R_{TMR} then,

$$R_{TMR} = R_N^3 + 3R_N^2 (1-R_N) = 3R_N^2 - 2R_N^3 \qquad (1)$$

Another parameter for evaluating the reliability of the system is the reliability improvement factor or RIF which is the ratio of the possibility of failure on non-redundant system and redundant system in a specific work time. If the RN and RR are non-redundant system reliability and redundant systems reliability then,

$$RIF = \frac{1 - R_N}{1 - R_{TMR}} \qquad (2)$$

If the failure rate of the sensor is 0,049 failure/10^6 hours, mission time t = 3.10^6, then the reliability of the sensor is $R_N = e^{-\lambda t} = e^{-(0,049)(3)} =$ 0.8633. If redundant sensors are used, the reliability increased to R_{TMR} = 0.9490. RIF value in this example is 2.6804. Figure 13 shows the reliability curve of one sensor and redundant sensors.

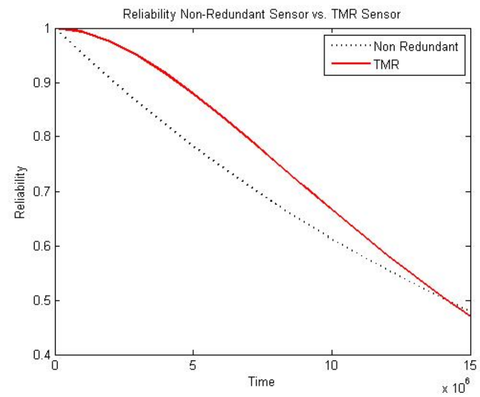


Figure 13. Reliability curves of non-redundant sensor and the TMR redundant sensors.

From the Figure 13 can be seen that the TMR redundant sensors is more reliable up to about 13,000,000 hours. After a very long usage, the performance of TMR redundant sensors down. At this time two sensors of the three sensors have failed that resulted the TMR redudant sensor performance falls below non redudant sensor.

3.5 Accuracy Sensor

In addition to increase reliability, redundant sensors also increases the accuracy of the sensor. In Figure 11 can be seen that the sensor output of three selected single sensor output which is the mid value. Selection of the sensor output which is the mid value can increase accuracy of the redundant sensor. When the sensor output suddenly increased, for example in Figure 11 occur at the output of sensor 2, then output the selected sensor is replaced with another. This mechanism will prevent the system from sensor readings are incorrect or in other words the accuracy is higher.

4. Conclusion

Redundant sensor using TMR configuration can to improve system reliability. Selection of the sensor output by using the mid value technique can be implemented in hardware using analog and digital components.

In addition to improving reliability, redundant sensors with TMR configuration also increases the accuracy of the sensor.

References

[1] Mawahib Gafare Abdalrahman Ahmed, Abdallah Belal Adam, John Ojur Dennis, and Gail Sylvia Steele, "Capacitor Device for Air Bubbles Monitoring", *International Journal of Electrical & Computer Sciences IJECS*, Vol: 9 No: 10, 2009.

[2] M. D. Krstic, M. K. Stojcev, G. Lj. Djordjevic, and I. D. Andrejic, "A Mid-Value Select Voter", Faculty of Electronic Engineering, University of Nis, Beogradska 14, 18000 Nis, Serbia & Montenegro, *Microelectronics and Reliability* Volume 45, Issues 3-4, March-April 2005, Pages 733-738

[3] Mark Stringham, B.S., M.S., P.E., "Reliability Analysis of Moog Ultrasonic Air Bubble Detectors", Moog, Inc., 2009.

[4] Carl Carmichael, "Triple Module Redundancy Design Techniques for Virtex FPGAs", XAPP197 (v1.0.1), 2006.

[5] Richard Spillman, "Lecture 26 – Alternative Architectures", Pacific Lutheran University.

[6] A. Namazi, S. Askari and M. Nourani, "Highly Reliable A/D Converter Using Analog Voting",*IEEE*,2008