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Significant Reliability Improvement of NMR Systems

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***Abstract*— Majority voted redundancy is increasingly implemented in fault-tolerant design today. In this technique, a voter receives parallel bits from an odd number of digital components and votes for the majority. Reliability improvement is the main focus of every fault tolerant system design. In this paper, we first present a viable alternative to the voting redundancy concept in order to significantly increase the reliability of conventional voting systems for five parallel components or higher. Then, an implementation of this novel concept is described.**

***Keywords*— Reliability; fault tolerance; redundancy.**

I. Introduction

Any system which could function correctly while there exist some faults in it is called a fault tolerant system. Some reasons to build fault tolerant systems are harsh environments, novice users, high repairing costs, and large systems which should always be kept up. Adding redundant components or functions is the most common approach to acquiring fault tolerant systems. When designing a fault tolerant system, several features need to be evaluated and a trade-off among them is required. These features include cost, weight, volume, reliability, and availability. In general, reliability is the most important feature and is defined as the probability of no failure in a given operating period.

Several techniques are available for introducing redundancy and hence improving system reliability. Underlying all these techniques is providing parallel paths to allow the system to continue its operation even when one or more paths fail. The system is called a ”parallel system” when all parallel components are powered up, and it is called a ”standby system” when only the online component is powered up and the rest are powered down. Practically, in any parallel system, a circuitry, called coupler or switch, is needed to implement redundancy. Couplers reconfigure various parallel components of the system after a detected failure. Since the coupler is added in series to the parallel components, its reliability significantly affects the reliability of the whole system.

A well-known technique to improve fault tolerance is voting redundancy. Applied to digital systems, voting redundancy takes advantage of the digital nature of elements' outputs to alleviate the problems associated with couplers or switches in parallel or standby systems.

Implementation of voting redundancy concept, called N-modular redundancy (NMR), is shown in Fig. 1. This system consists of $2n+1$ parallel digital circuits ($n \geq 1$), all having equivalent logic (generally, identical digital circuits) with the same input applied to all elements. A voter is put in series with the parallel digital components and the outputs of the circuits are compared by the voter and the majority is given as the system output. If more than half of the digital elements work properly, the voter will decide correctly.

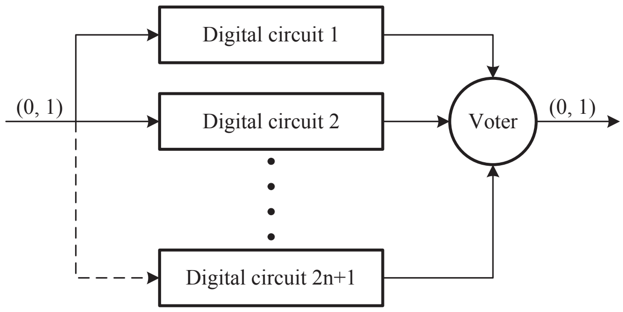

Figure 1. Majority voting.

In classical NMR systems, a higher reliability is only achieved within a specific mission time. The length of the mission time and the system reliability within this time period are dependent on component failure rates and the number of parallel components respectively; improving the failure rates of the parallel components will extend the mission time, and increase of the number of components will result in a larger system reliability value within the mission time. Once the mission time is over, the reliability plummets. In system designs using the classical majority voters, one must carefully evaluate the values of reliability obtained over the time from ”zero” to ”maximum mission time,” for various numbers of parallel components and failure rate values, and ensure that the voting system will not be used after this maximum mission time.

In this paper, we will propose a new idea to increase the reliability of NMR systems significantly for the systems with five or more parallel components. In order to implement our novel concept, a front end circuit with special features should be designed. One such implementation will also be explained. Throughout this article, we assume that the parallel digital components are identical and have the same constant failure rate λ, the system is nonrepairable, and that the voter (in classical design) or front end circuit (in our novel design) do not fail.

II. Classical NMR Systems

NMR systems were first introduced and discussed in the 1960s [1], [2]. The basic NMR system is called triple modular redundancy (TMR). TMR is the most common implementation of majority voting systems due to its lower cost. It consists of three parallel digital components (modules), all of which have equivalent logic and the same truth tables. The same input is fed to the three modules and a voter gives the majority as the system output. One usage of TMR is for the protection of combinational and sequential logic in reprogrammable logic devices, called Functional Triple Modular Redundancy (FTMR) [4].

If any two of the three modules in the TMR system work, assuming the voter does not fail, the system output will be correct. This equals the reliability of a two-out-of-three system. Thus, the reliability of a TMR system, R_{TMR}, based on the reliability of a module, p, is

$$\begin{aligned} R_{\text{TMR}} &= B(3:3) + B(2:3) \\ &= 3p^2 - 2p^3, \end{aligned} \tag{1}$$

where B is the binomial (Bernoulli) distribution.

If we assume a constant failure-rate λ for each module and a perfect voter for the TMR system, then each module will have the reliability $p = e^{-\lambda t}$, and the reliability of the network will be

$$R_{\text{TMR}} = 3e^{-2\lambda t} - 2e^{-3\lambda t}. \tag{2}$$

As the cost of digital circuits are reduced, NMR systems with higher number of replicated digital components gain popularity to increase the fault tolerance of systems further. For a system consisting of $2n+1$ parallel digital circuits and a perfect voter, the reliability without repair is

$$\begin{aligned} R_{\text{NMR-Classic}} &= \sum_{i=n+1}^{2n+1} B(i:2n+1) \\ &= \sum_{i=n+1}^{2n+1} \binom{2n+1}{i} p^i (1-p)^{2n+1-i}, \end{aligned} \tag{3}$$

where p is the success probability (reliability) of any digital circuit. Equation (3) is in fact the reliability expression for an "$n+1$ out of $2n+1$" system.

For an NMR system containing $2n+1$ circuits, as n is increased, the reliability is increased too but only within the region of primary interest, $0 < \lambda t < 0.69$, where λ is the constant failure rate associated with every parallel component [1], [3]. Outside this region, the reliability is decreased. The maximum mission time of a system should be when its λt reaches the value of 0.69. Equation (3) is plotted in Fig. 2 (with each parallel circuit having the success probability of $e^{-\lambda t}$) as a function of mission time, λt, where λ is assumed to be unity.

III. A Novel NMR System Design

In the classical NMR system design, as long as $n+1$ or more out of $2n+1$ components are operating, the system will be functional. In this design, no attempt is made to detect the failed components and eliminate them from the voting process.

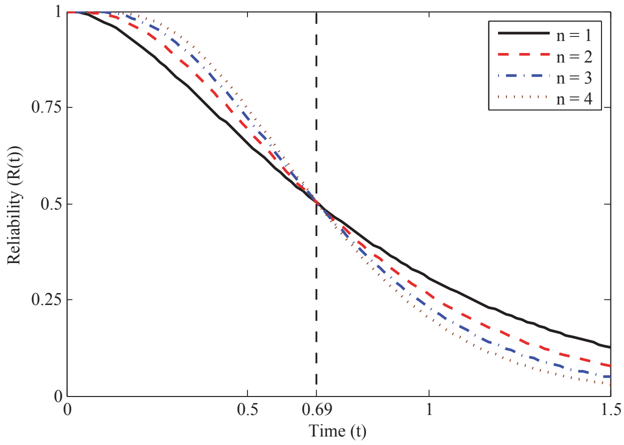

Figure 2. Reliability of a classical majority voter containing $2n+1$ circuits.

In this article, we propose a novel idea to increase the reliability of the classical NMR systems which was expressed in (3). The new concept is to change the size of the NMR system each time a redundant component fails: if the failed component is singled out and removed from the NMR system, a new system with fewer total number of parallel components will be created with all the components functioning. In other words, instead of keeping the original larger system including the failed and operating components ($2n+1$ circuits in total), each time a component fails, the system is made smaller including only the operating components. While in the classical method, the NMR system will produce correct outputs for as long as at least $n+1$ of $2n+1$ are operating, in our novel idea, the system will be functional as long as at least 2 components are operational. The reliability of the system will be

$$\begin{aligned} R_{\text{NMR-Novel}} &= \sum_{i=2}^{2n+1} B(i:2n+1) \\ &= \sum_{i=2}^{2n+1} \binom{2n+1}{i} p^i (1-p)^{2n+1-i}. \end{aligned} \tag{4}$$

The extra reliability gained using this design compared to the classical one is significant. For a TMR system, no improvement is made. For a five modular redundancy system, the reliability will be $B(2:5)$ higher than that of the classical one. As the number of parallel components goes higher, the additional reliability will be much higher. Equation (4) is plotted in Fig. 3 under the same assumptions stated for Fig. 2. The higher reliability of this design for NMR systems with five or more parallel components is evident in this Figure.

The new fault tolerant system design requires a special front end circuit to replace the classical voter. This circuit should have the following characteristics:

- It should single out a failed component and remove it from the system;
- It should record the state of the components (failed or operative) in a status register;

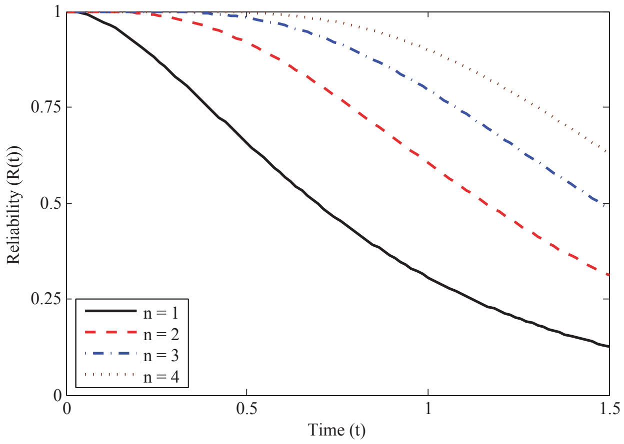

Figure 3. Reliability of our novel NMR system design containing $2n + 1$ circuits.

- The contents of the status register should be stored in an EEPROM at every system power-down and retrieved at every system power-up, so that the failed items remain disconnected after a system power-up.

In the following Section, an example implementation of the front end circuit with the above characteristics will be detailed.

IV. Example Front End Circuit for Higher Reliability Gain

As mentioned before, to design an NMR system with higher reliability, a special front end circuit should be employed. An example circuit for a system with five parallel components is illustrated in Fig. 4. This circuit could be easily extended for higher number of parallel components.

The components used in this example design are: non-inverting active-high enable and non-inverting active-low enable three-state buffers, XOR and AND and OR gates, and a 5-bit latch. The latch (also called status register) is initialized to 00000 and is used to control the three-state buffers and also keep the status of the parallel components to be saved in an EEPROM when the system is down. A zero in every bit position of the status register indicates that the corresponding parallel circuit is operative and a one indicates failure. A "non-inverting active-low enable" three-state buffer, connected to every digital circuit, puts the output line in high-impedance when the digital circuit fails to operate correctly. A circuitry is also needed to detect the failed parallel component. Assuming that only one component fails at a time, if the output of a parallel component disagrees with the outputs of its both operational adjacent components, it is considered failed and should be removed from the system by flipping its corresponding bit in the status register on. Therefore, the output of a parallel component should be XORed once with the output of its operational left-hand side circuit and once with its operational right-hand side circuit. The AND of these two XOR operations will be one if the circuit has failed to operate properly, and this output should be used to update the status register. Once a bit in status register is turned one, it should retain this value forever. The only complication is when the adjacent component for comparison is failed; the three-state buffers at the inputs of the XOR gates in Fig. 4 facilitate the comparison with the immediate *operative* left-hand or right-hand side neighboring circuits.

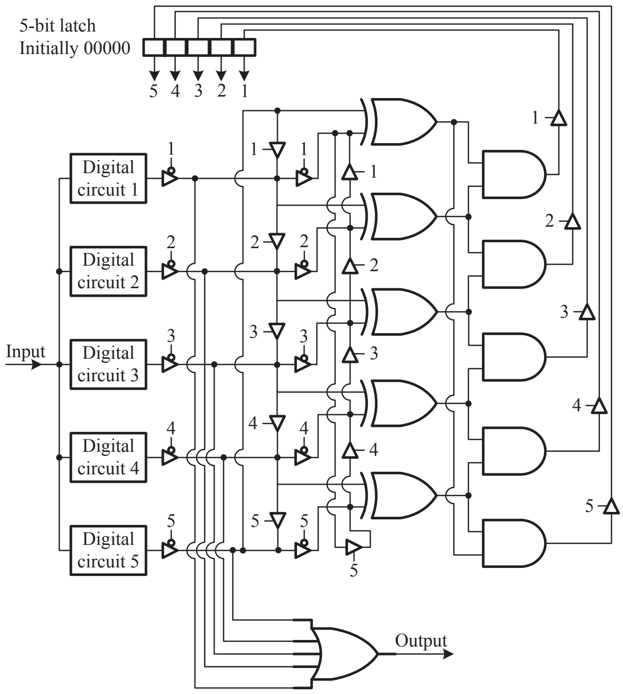

Figure 4. An example front end circuit to obtain higher reliability.

The correct output of this example circuit is available only after the failed component is detected and the status register is updated, hence putting the failed component's output in high-impedance state. Therefore, the output of this front end circuit should be read once it is stabilized. If the NMR system is part of a clocked synchronous machine, the worst-case path through the front end circuit should be considered when deciding on the clock period. In the case of an asynchronous design, the stabilization problem can easily be resolved by placing the final circuit output in a one-bit flip-flop controlled by a clock.

In Fig. 4, the final output is the OR of the outputs from the parallel circuits. An AND gate could be used in place of OR gate too. However, these outputs cannot be tied together; while a failed item is being detected and the circuit is being stabilized, if the components were to drive a shared line at same time, and if they were trying to maintain opposite output values (0 and 1), then excessive current would flow and create noise in the system.

V. Conclusion

Voting redundancy is the most common fault tolerant design technique used for digital systems. While the reliability obtained by TMR systems is reasonable, the addition of more parallel components will increase the reliability negligibly. Even worse, after a known duration of time, a system with higher number of parallel components will be less reliable than the one with lower number of components. In this article, we proposed a novel fault tolerant design to address these drawbacks of the classical voting design.

While our proposed technique significantly improves reliability, it adds some complexity to the front end circuit, and also requires the status of the parallel elements to be known after every possible system shut-down. Although the complexity of the front end circuit may be reduced through another more efficient implementation, saving the latest status register contents in a non-volatile memory for future use cannot be eliminated.

REFERENCES

[1] J. K. Knox-Seith, A Redundancy Technique for Improving the Reliability of Digital Systems. Stanford University, Stanford, CA: Stanford Electronics Laboratories, 1963.

[2] W. H. Pierce, Improving Reliability of Digital Systems by Redundancy and Adaptation. Stanford University, Stanford, CA: diploma thesis, 1961.

[3] M. L. Shooman, Reliability of Computer Systems and Networks: Fault Tolerance, Analysis, and Design, 1st ed., vol. 1. Hoboken, NJ: Wiley-Interscience, 2002, pp. 154–155.

[4] S. Habinc, Functional Triple Modular Redundancy (FTMR), Design and Assessment Report. Goteborg, Sweden: Gaisler Research, 2002.