A Radiation-Hardened R-2R DAC Utilizing a Novel Compensated Switching Technique for Linearity Improvement

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1. Introduction

Digital-to-Analog Converters (DACs) are essential components for bridging the digital and analog domains in nuclear power plant applications, including instrumentation, control, and measurement systems. In high-radiation environments, such as those encountered during severe accident conditions, electronic components are exposed to total ionizing dose (TID) effects. TID-induced trapped charges cause shifts in the threshold voltage (V_{th}) of MOS devices, leading to changes in the switch on-resistance [1–4]. This R_{on} variation disrupts the ideal resistance ratio of the DAC, resulting in output voltage deviations and differential non-linearity (DNL) errors.

2. Principle of R-2R DAC and R_{on} Dependency

An N-bit R-2R DAC utilizes a symmetrical resistor ladder network to generate binary-weighted analog outputs. To illustrate the fundamental vulnerability of this architecture, a simplified 4-bit R-2R DAC structure is illustrated in Fig. 1. The operational accuracy of this network relies on ideal switching conditions where the switches connecting the R-2R segments to the reference voltage or ground exhibit zero resistance.

In practical implementations, each switching element inherently possesses a finite on-resistance (R_{on}). As depicted in the 4-bit model, this R_{on} acts in series with the 2R segments, disrupting the ideal impedance ratio. The impact can be quantified through Thévenin equivalent analysis at the MSB node. For a reference voltage of 1.6 V and R = 1 kΩ, the mid-range output voltage under ideal (R_{on} = 0 Ω) and non-ideal (R_{on} = 200 Ω) conditions is compared as follows:

$$R_{on} = 0\Omega:\ R_{eq} = (2k \parallel 2k) + 1k = 2k\Omega$$
$$V_{out} = 0.8V(ideal)$$
$$R_{on} = 200\Omega:\ R_{eq} = (2.2k \parallel 2.2k) + 1k = 2.1k\Omega$$
$$V_{out} \approx 0.775\ V \qquad (1)$$

As shown in Eq. (1), even a moderate R_{on} of 200 Ω reduces the mid-range output by approximately 3.1%. This structural mismatch degrades both the output voltage accuracy and the DNL performance. The vulnerability is further amplified when radiation exposure induces dynamic R_{on} fluctuations through TID-induced threshold voltage shifts in MOS devices [1, 2].

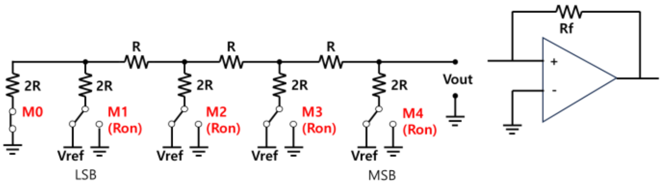

Fig. 1. Simplified 4-bit R-2R DAC structure illustrating the series connection of R_{on} with 2R segments.

3. Evaluation of R_{on} Variations under Gamma Irradiation

The relationship between radiation-induced R_{on} variations and linearity was systematically analyzed using two types of DAC structures with differing switch resistances: a high- R_{on} DAC and a low-R_{on} DAC. Both structures were fabricated and experimentally evaluated under a gamma irradiation environment. The high-R_{on} DAC employed scaled switch geometries to mitigate radiation-induced V_{th} shifts, while the low-R_{on} DAC served as a reference with standard switch dimensions. Irradiation tests utilizing a ^{60}Co gamma source up to a TID of 22.987 kGy revealed that the full-range output voltage drift of the high-R_{on} DAC was suppressed to 1.035%, whereas the low-R_{on} DAC exhibited a drift of 8.873%.

The increased baseline resistance in the high-R_{on} structure correlated with a degradation in linearity performance, occurring in parallel with the mitigated voltage drift. As illustrated in Fig. 2, the measured worst DNL of the high-R_{on} DAC increased to 10 LSB during the irradiation test. This experimental observation indicates that structural scaling for drift reduction alone is insufficient for maintaining overall DAC performance. The resistance mismatch caused by the high R_{on} requires a systematic compensation approach to preserve linearity under radiation exposure.

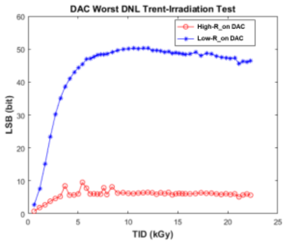

Fig. 2. Degradation of the worst DNL in DAC during ^{60}Co gamma irradiation

4. Proposed Compensated Switching Technique

A compensated switching architecture is proposed to resolve the fundamental resistance mismatch identified in the irradiation evaluations. Instead of merely modifying the physical dimensions of the switches for drift reduction, the proposed design introduces a resistance ratio matching mechanism. As conceptually illustrated in the overall block diagram of Fig. 3, a matched compensation element is incorporated into the R-segment to match the on-resistance of the 2R-branch. This symmetric configuration ensures that the critical R to 2R impedance ratio remains robust against radiation-induced threshold voltage (V_{th}) shifts. Furthermore, the switch on-resistance is fundamentally dependent on the gate-to-source overdrive voltage (V_{gs} - V_{th}). Maintaining a constant R_{on} requires stable V_{gs} conditions during dynamic switching operations.

The proposed DAC addresses this vulnerability by employing a dynamic biasing loop that tracks source-voltage fluctuations and actively stabilizes the V_{gs} applied to the compensation elements. Integrating this symmetric resistance matching with the dynamic voltage tracking method provides a systematic resolution to linearity degradation, preserving the overall accuracy of the DAC under TID exposure.

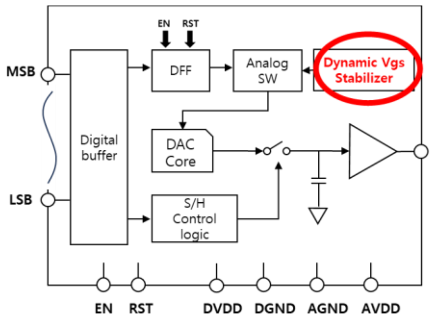

Fig. 3. Overall architecture of the proposed compensated DAC integrating the dynamic V_{gs} stabilization technique.

5. Simulation Results

A circuit-level simulation was conducted to evaluate the performance of the proposed compensated switching architecture under varying R_{on} conditions, emulating radiation-induced degradation. In this evaluation, the on-resistance was swept from 10 Ω to 1 kΩ to represent progressive TID exposure.

As demonstrated in the full-range and middle-range magnified output comparisons of Fig. 4(a) and 4(b), the uncompensated reference DAC exhibited a substantial output voltage deviation during the middle-code input state, dropping from the ideal 0.8 V to 0.69 V at the elevated R_{on} condition. In contrast, the proposed compensated architecture maintained a strict and stable output of 0.8 V across the entire R_{on} variation range.

This stable voltage output directly correlated with the preservation of linearity. Under the most severe condition (R_{on} = 1 kΩ), the uncompensated reference DAC exhibited a mid-range output of 0.69 V, representing a 13.75% deviation from the ideal 0.8 V, with corresponding severe DNL degradation. In contrast, the proposed compensated architecture maintained the ideal output across the entire R_{on} range, preserving the DNL within the 1 LSB threshold. The simulation results demonstrate that integrating the structural compensation element with the dynamic biasing mechanism systematically prevents radiation-induced linearity degradation.

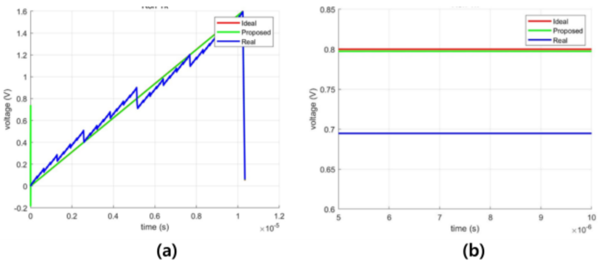

Fig. 4. Simulated output voltage comparison under an elevated R_{on} condition of 1 kΩ: (a) full-range output and (b) middle-range magnified view.

6. Conclusion

This study presented a compensated switching architecture for R-2R DACs to resolve linearity degradation caused by radiation-induced R_{on} variations. By introducing a symmetric resistance ratio matching mechanism combined with a dynamic V_{gs} stabilization technique, the fundamental impedance mismatch is equalized. Simulation evaluations confirmed that the proposed design maintains strict output accuracy and DNL performance under emulated high-radiation conditions. The proposed architecture provides a systematic methodology for ensuring reliable analog-digital interfacing in extreme environments, encompassing nuclear power plant instrumentation and control systems.

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