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EMI RADIATED FROM THE PCB DESIGN SINGLE ENDED AND DIFFERENTIAL ENDED

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ABSTRACT

Electromagnetic Interference (EMI) is a significant challenge that affects signal integrity in modern high- speed and mixed-signal electronic circuits. This project presents a comparative analysis of EMI radiation between single-ended and differential-ended transmission methods. The circuits were designed and simulated using Proteus software, where both single- ended and differential-ended configurations were implemented to observe the oscilloscope readings. The waveform-based EMI and EMC characteristics were further analysed using LT-spice, where the signal generation and field variations were studied to understand radiated emission behaviour. The results clearly show that differential-ended signalling offers superior noise immunity and lower electromagnetic emission levels compared to single-ended transmission. This is primarily due to the balanced current flow that causes mutual field cancellation. The study highlights that adopting differential pair design and proper PCB layout practices are crucial for minimizing EMI in embedded and communication systems.

1. INTRODUCTION

The growing complexity and miniaturization of modern electronic systems have made Electromagnetic Interference (EMI) one of the most critical challenges in circuit design. EMI occurs when unwanted electromagnetic energy from one circuit or component affects the operation of another, leading to signal distortion or system malfunction. The method of signal transmission plays a key role in determining the level of EMI generated by a system. In single- ended transmission, the signal is carried on one line and referenced to a common ground. This configuration is simple but highly prone to noise coupling and ground potential variations which can increase radiated emission. On other hand, differential transmission utilizes two complementary signal lines carrying equal and opposite voltages. This arrangement provides natural cancellation of common-mode noise, resulting in improved noise immunity and lower EMI radiation. In this study, both single-ended and differential-ended circuits were designed and simulated using Proteus software to observe oscilloscope outputs and verify signal behaviour. To further visualize the PCB implementation, Easy EDA was used to design the 2D PCB layout and 3D structural model of the differential transmission system. Additionally, LT-spice simulations were performed to analyze waveform responses and evaluate EMI and EMC characteristics in the frequency domain. The objective of this work is to comparatively analyze EMI behaviour in single-ended and differential- ended configurations, identify how balanced differential signalling reduces radiated noise, and develop practical PCB layout strategies to minimize EMI in embedded and communication circuits.

2. METHODOLOGY

The proposed study follows systematic methodology comprising three primary stages: circuit simulation, PCB layout design, and EMI performance evaluation. Both single-ended and differential- ended transmission circuits were developed, simulated, and analyzed under identical operating conditions to ensure a fair comparison. Initially, the circuit schematics were designed in Proteus Design Suite, which provided a simulation environment for observing signal waveforms and identifying noise susceptibility in each configuration. The oscilloscope tool in Proteus was employed to monitor the signal amplitude, phase characteristics, and waveform integrity during transmission. This stage helped to identify the how single-ended and differential-ended systems respond to noise coupling and signal distortion.

Subsequently, the designed circuits were transferred to Easy EDA for PCB layout creation and 3D visualization. The Easy EDA environment enabled the implementation of proper routing techniques, controlled trace lengths, and optimized ground plane design. Both 2D and 3D PCB views were generated to analyze the physical layout, ensuring that the differential pair traces were routed symmetrically for balanced signal transmission and minimal EMI radiation. Finally, the EMI and EMC analysis was performed using LT- spice simulation software. The time-domain and frequency-domain responses were observed to evaluate radiated emission behavior and quantify the noise reduction achieved through differential signaling. Comparative results between single-ended and differential-ended configurations were obtained in terms of waveform distortion, signal-to-noise ratio, and common-mode noise

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rejection. This integrated methodology enables a comprehensive understanding of EMI generation mechanisms, differential noise cancellation effects, and PCB-level design optimizations essential for achieving electromagnetic compatibility in embedded and communication systems.

3. RESULT AND DISCUSSION

The experimental comparison between single-ended and differential-ended transmission circuits was carried out through simulation and PCB-level analysis. Both configurations were simulated under identical conditions to evaluate their susceptibility to electromagnetic interference and overall signal integrity. In the single-ended circuit, noticeable waveform distortion and amplitude fluctuations were observed during Proteus simulation. Because the signal and return paths shared a common ground, the circuit exhibited significant noise coupling and ground-induced voltage variations. The radiated interference was clearly visible in the oscilloscope output, indicating higher susceptibility to EMI.

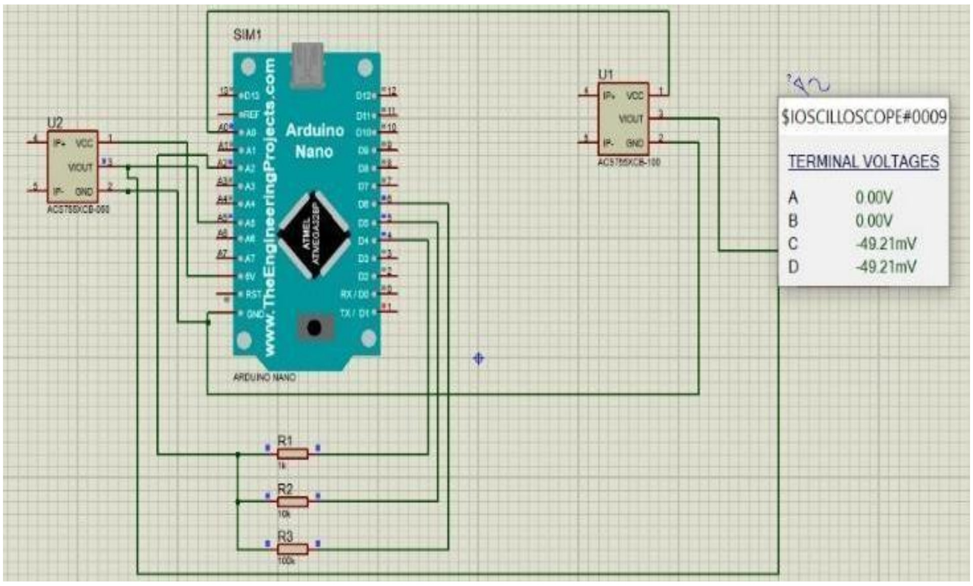

Fig 1: Proteus Simulation of Single-Ended Circuit

Conversely, the differential-ended circuit demonstrated a stable and distortion-free output under the same test conditions. The equal and opposite signals carried along the two traces effectively cancelled common-mode noise, resulting in a clean waveform and improved noise immunity. This confirmed that differential signaling significantly reduces EMI and enhances signal stability.

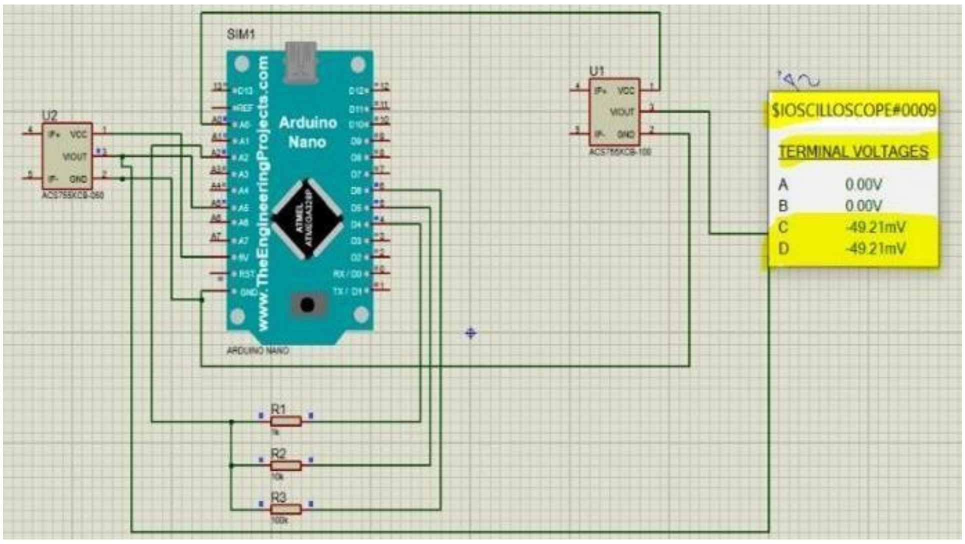

Fig 2: Proteus Simulation of Differential- Ended Circuit

Following the simulation phase, both circuit configurations were implemented as Printed Circuit Boards (PCBs) using Easy EDA. The single-ended layout exhibited longer unshielded traces and tighter coupling between signal and ground paths, which can increase electromagnetic emissions. In contrast, the differential-ended PCB layout employed paired routing, continuous ground pours, and controlled trace spacing, all of which minimized parasitic capacitance and inductance, thereby reducing radiated noise.

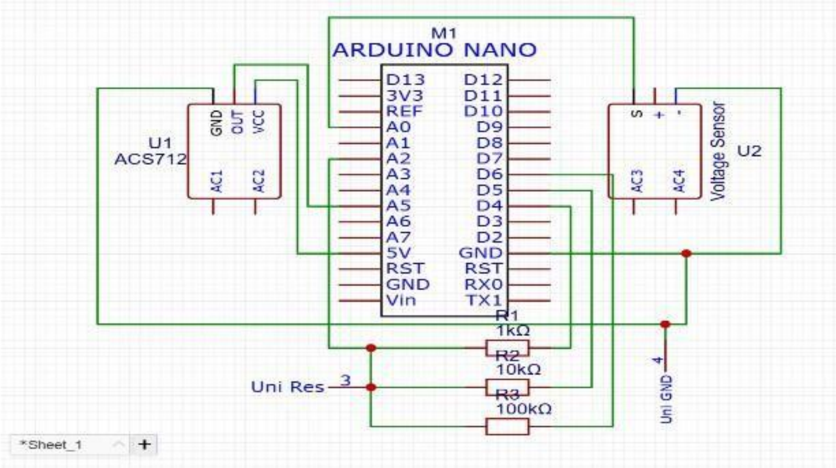

Fig 3: Easy EDA Layout of Single-Ended Circuit

The 3D PCB model generated in Easy EDA visually confirmed the optimized component placement and mechanical consistency. The symmetrical routing of differential pairs, proper ground connections, and shielding arrangements were clearly visible, ensuring that the physical layout adhered to EMI reduction guidelines.

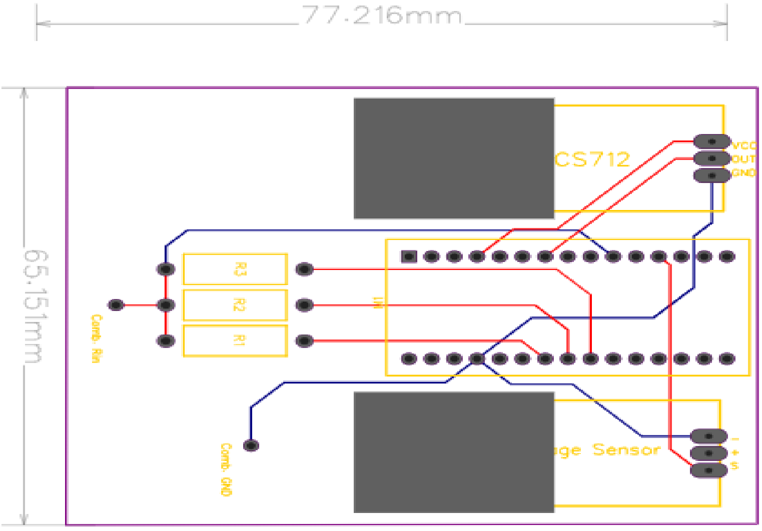

Fig 4: 2D PCB Model of Differential Circuit

During practical design optimization, several EMI control techniques were implemented. RC low-pass filters (1 kΩ and 100 nF) were added to the analog inputs to suppress high-frequency noise. Series resistors (22 Ω– 47 Ω) were connected to high-speed digital outputs to mitigate signal ringing and reflection. Ground pours were maintained around sensitive analog and mixed-signal traces to control radiated paths. Furthermore, analog and digital components were physically separated to reduce cross-domain interference, and ferrite beads were introduced at connector interfaces to limit conducted noise.

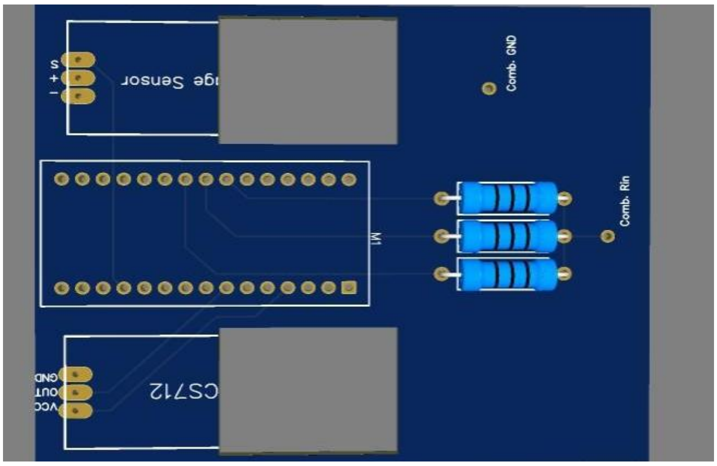

Fig 5: 3D PCB Model of Differential Circuit

The two signals, being equal in magnitude and opposite in polarity, achieved effective common-mode noise cancellation, resulting in significantly reduced EMI emission. The combined analysis confirms that differential-ended signaling, supported by optimized PCB layout and EMI mitigation techniques, achieves demonstrates the importance of adopting balanced transmission and good layout practices in modern mixed-signal and embedded systems.

LT-spice Simulation and EMI Analysis

To further analyze the electromagnetic behavior of the designed circuits, both single-ended and differential- ended configurations were recreated in LT-spice for time-domain and frequency-domain analysis. The primary objective was to observe how signal integrity, harmonic distortion, and spectral distribution differ between the two transmission methods. The single- ended circuit exhibited higher harmonic content and amplitude variations in the frequency spectrum, confirming its greater susceptibility to EMI. The waveform output showed noticeable ringing and transient spikes caused by the common ground return path.

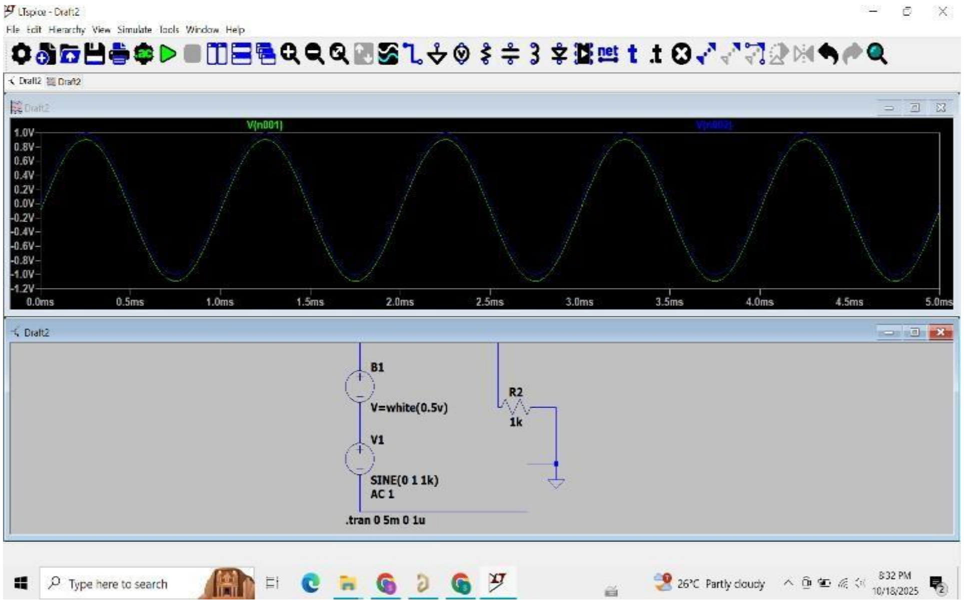

Fig 6: LT-spice Output Waveform of Single-Ended Circuit

In contrast, the differential-ended circuit produced clean and symmetrical waveforms with lower harmonic amplitude and minimal spectral leakage. The two signals, being equal in magnitude and opposite in polarity, achieved effective common-. cancellation, resulting in significantly reduced EMI emission.

The FFT (Fast Fourier Transform) analysis in LT-spice further confirmed that differential signaling reduced the overall noise power density and harmonic distortion levels. This demonstrates that balanced differential transmission not only enhances signal integrity but also contributes to improved electromagnetic compatibility (EMC) performance.

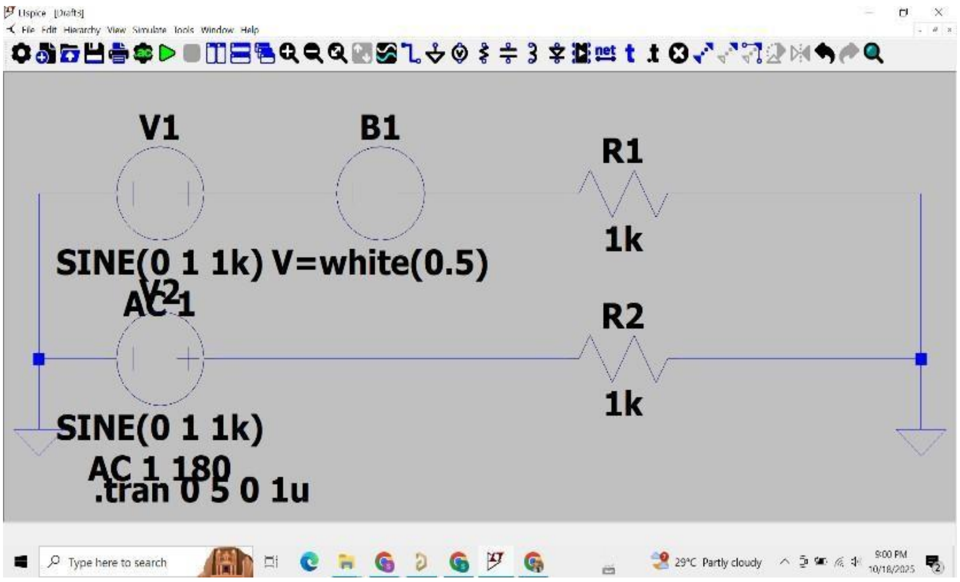

Fig 7: LT-Spice Output Waveform of Differential- Ended Circuit

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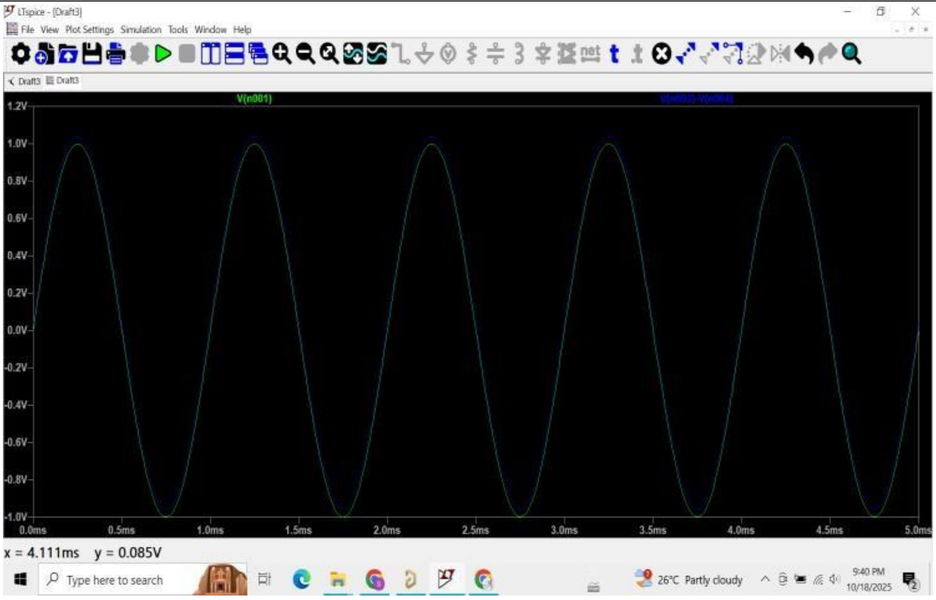

Fig 8: LT-Spice Output Waveform of Differential- Ended Circuit

4. FUTURE SCOPE

Further research can extend this work into experimental validation through hardware testing using a spectrum analyzer and near-field probes to measure actual EMI levels. Incorporating LT Spice simulation for transient EMI waveform analysis can provide deeper insight into frequency-domain characteristics. Future designs can also explore differential impedance control, shielding effectiveness, and crosstalk analysis to optimize real- world EMI/EMC performance in embedded and communication system applications.

5. CONCLUSION

This work successfully demonstrated the comparative analysis of single-ended and differential-ended circuits with respect to electromagnetic interference (EMI) performance. Simulation and PCB layout evaluation confirmed that differential signaling provides superior noise immunity and improved signal integrity under identical test conditions. The balanced transmission in differential circuits effectively cancelled common- mode noise and minimized radiated emissions, leading to cleaner and more stable output responses. Furthermore, the incorporation of EMI control strategies such as RC filtering, ground pours, series termination resistors, and ferrite bead isolation contributed to enhanced electromagnetic compatibility (EMC). The combined experimental and design validation established that differential-ended configurations are more suitable for high-speed and mixed-signal applications where electromagnetic performance is critical. Future extensions of this study can include hardware-level EMI measurements and analysis of differential line impedance matching for further optimization.

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