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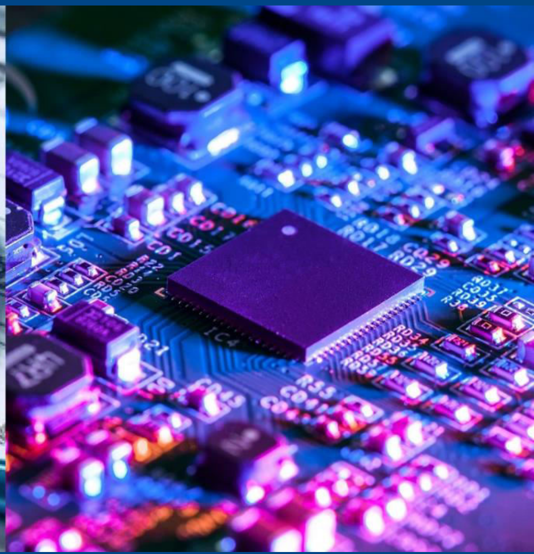

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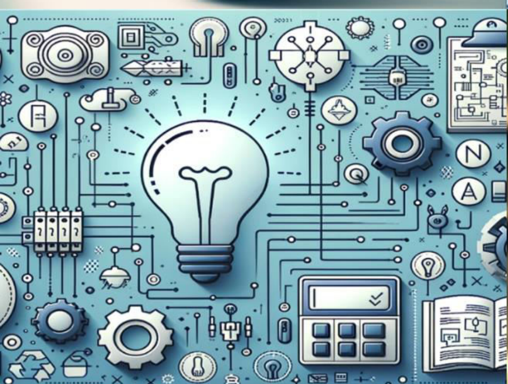

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From Circuits to Systems: A Review of How Electronic Design Enables Modern Electrical Engineering

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ABSTRACT: An electronic circuit is an integral part of electrical engineering, and it forms the technological basis of systems, which are used in communication, medicine, robotics, the automotive industry, household appliances, industrial automation and smart infrastructure. This paper summarizes the evolution of electronic design from simple circuits and discrete components to integrated, embedded, connected and intelligent engineering systems. The review is conducted through a secondary research method (literature search) using scholarly literature retrieved from Google Scholar with the latest publications in the last five years (2020–2025). The five key themes studied are: the transition from circuit design to system-level engineering; miniaturisation and integrated circuits; embedded systems, sensors and the Internet of Things; low power electronics and advanced semiconductor technologies; intelligent and edge electronics. The review shows how advancements in the electronic circuit design have helped enhance the performance, functionality, energy efficiency, miniaturisation, and processing capacities of the electronic system. But, the greater complexity of technology brings challenges in terms of reliability, thermal management, cyber security, manufacturing, cost and system integration. The results show the necessity of a holistic engineering approach in which innovations at the circuit level are taken into account with overall system needs. Overall, the transition from circuits to systems demonstrates the continuing importance of electronic design in shaping the development and future direction of modern electrical engineering.

KEYWORDS: Electronic Circuit Design; Integrated Systems; Modern Electrical Engineering

I. INTRODUCTION

Electronic circuit design is an essential component of contemporary electrical and electronic engineering, which supplies the basic blocks used to control, process, transform and move electric signals. Advances in electronic design have given rise to more and more complex technological applications, from simple circuits using resistors, capacitors and transistors to more complex circuits with microcontrollers, sensors, and integrated circuits. (Kassakian et al., 2023). The effective and dynamic functioning of these components is crucial to the successful operation of modern engineering systems, providing the performance, reliability, efficiency, and functionality that are needed. Semiconductors and integrated circuits have also helped to reduce the size of electronic devices and enhance the computing power and energy efficiency of a wide range of applications. The significance of circuit design is not confined to the individual circuits or components; engineers are now more concerned with how circuits will function within the overall system. It is seen in embedded electronics, communication technologies, robotics, medical devices, automotive systems, consumer electronics and smart infrastructure, among others, all as systems. Therefore, when we design an electronic system, we need to be concerned about the power consumption, scaling, cost, reliability, and performance (Harris and Harris, 2021). The paper discusses the evolution of circuit design to system-level engineering, covering the important role of electronic components and design in today's technological systems and the future impact of new developments in embedded and edge electronics.

II. RATIONALE AND OBJECTIVE

Rationale

This paper is motivated by the fact that in the design of modern electrical engineering systems electronic circuits have become more and more important. Through the understanding of how individual component works together they will be given a basis to analyse more complex technologies such as embedded systems, robotics, communication devices, medical equipment, automotive electronics and smart infrastructure (Ikpe et al., 2024). The field of engineering is becoming more and more miniaturized, low-power, intelligent processing and connected systems, so there is a need to

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consider the impact of circuit level design on overall system performance. This paper is therefore a review of the fundamental electronic design principles that enable the development, efficiency, reliability and scalability of modern engineering systems.

Objectives

1. To investigate the basic concepts of an electronic circuit design and the functions of basic components such as resistors, capacitors, transistors, sensors, microcontroller and integrated circuits.
2. To understand the integration of electronic circuits in today's engineering systems such as communication, embedded, robotics, medical, consumer electronics, automotive, and smart infrastructure.
3. To assess the impact of the evolution of electronic design such as miniaturisation, low-power electronics, embedded systems and edge electronics on the performance, efficiency, reliability, scalability and development of modern electrical engineering.

III. METHODOLOGY

The research methodology of this research paper is secondary research, which is the literature study using Google Scholar as the source of the literature. The study has considered only academic research published after 2020 so as to get a sense of the latest developments in electronic circuit design and modern electrical engineering. The following keywords are used to identify relevant scholarly articles, peer-reviewed journal papers, conference publications and academic research: Electronic Circuit Design, Integrated Circuits, Embedded Systems, Low Power Electronics, Sensors, Robotics, Communication Systems, Medical Electronics, Automotive Electronics and Edge Computing. The literature identified will be reviewed and analysed to determine key developments, technological trends, applications, challenges and future directions. Special emphasis will be placed on the research that investigates the circuit level design aspects of the wider system level design aspects such as performance, energy efficiency, reliability, miniaturisation, scalability and system integration. Only sources that are relevant to the research objectives and available and credible scholarly publications through Google Scholar will be considered. Throughout the research process, ethical considerations will be observed by accurately representing findings of published works, avoiding plagiarism, citing all sources properly, and not misrepresenting or using information out of context. Since no humans are involved, and only secondary published literature is used, there are no risks associated with participant privacy or informed consent.

IV. LITERATURE REVIEW

Theme 1: Evolution from Electronic Circuits to Integrated and System-Level Design

Electronic circuit design is the basis of the fundamental technical design for modern electrical and electronic systems. The engineers at the circuit level design and combine transistors, capacitors, resistors, diodes and inductors together for specific purposes such as signal amplification, signal switching, signal filtering, energy conversion or signal information processing. But, with the advent of modern technology, the focus of engineers has been moving from circuit to highly integrated and interdependent systems (Pedroni, 2020). As semiconductor technology continues to be developed, many electronic functions can be built into a small, integrated circuit, which underpins microprocessors, microcontrollers, sensors, memory devices, and systems-on-chip. Recent literature shows that the growing complexity of designs has driven the need for more sophisticated electronic design automation (EDA) techniques. With the evolution of very large-scale integration (VLSI) technologies, the design of circuits has become more complex and newer optimization, performance, power consumption, and manufacturing variability issues have arisen. Since 2020, the utilization of computational and machine-learning approaches in EDA has thus been increasingly explored for tackling complex design problems (Chun et al., 2022). This illustrates an important trend in electrical engineering that circuit design is no longer restricted to the manual design of individual parts but is increasingly automated at several levels of the design hierarchy. The literature also indicates that it is crucial to think at the system level since the performance of the circuit has an impact on the final engineering product. The circuit can work as a standalone system but may not be able to meet the requirements of the complete system due to issues such as heat generation, power consumption, electromagnetic interference, communication delay, reliability, or physical constraints (Pan et al., 2025). Therefore, contemporary electronic engineering demands that the designers must take into account interactions among the components, software, power supply, communication interfaces, and environment. The transition from circuits to systems is especially significant in complex applications where several electronic functions have to function in real time together. This has led to a greater interdependence between electricity and other engineering branches such as computer engineering, materials science, communications,

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artificial intelligence, and control engineering, which has led to the evolution of circuit design. This interdisciplinary development has enabled electronic systems to become smaller, faster, more intelligent and more capable (Jørgensen et al., 2020). However, the more complex the system, the more difficult it is to verify the design, test the system, manage heat, ensure reliability, and produce the product. Design methodologies are thus emphasized which take account of not only individual circuit performance but also global system requirements, as described in the literature. The integrated circuit, miniaturisation and electronic design automation (Eda).

Theme 2: Integrated Circuits, Miniaturisation and Electronic Design Automation

The miniaturisation and integration of electronics components are important advances in the transition from traditional circuit design to modern engineering systems. The integrated circuits enable several electronic functions to be crammed into a small physical space, paving the way for miniaturized and powerful electronic devices (Yang et al., 2024). The development is especially significant in areas such as mobile technologies and technologies for consumer electronics, communication equipment, automotive systems, medical devices and industrial applications. With rising demands for functionality in smaller devices, design optimisation is becoming a main issue with modern electrical engineering. The increasing complexity of integrated circuit design has in recent research been shown to be a factor that has made EDA tools more important. These are used for various activities of the electronic design process ranging from circuit modelling and simulation to physical circuit design, verification, optimization, and testing. Increasing complexity of VLSI has stimulated researchers to explore intelligent solutions to challenging design problems using computational approaches and machine learning (Sazonov, 2020). This suggests that machine learning is being used in various stages of the EDA design chain, with an increasing trend towards automation and data-driven design. There are, however, important limitations in the literature. In advanced circuit design, there are a number of conflicting goals, and a change to improve one goal can have a detrimental impact on another. For instance, if a physical dimension is reduced, then there can be issues with thermal performance, and if the computational performance of a system is increased, then the energy consumption can also increase. Likewise, if the optimization is very aggressive, it can impact the reliability and/or manufacturing yield. Bayesian approaches for EDA have revealed how uncertainty and process variation are important factors to consider in an integrated circuit design (Zeng et al., 2023). These techniques are relevant because variations in manufacturing can affect circuit performance and reliability, and statistical modelling and optimisation of circuits are becoming increasingly important in the more advanced design of electronics. The integrated circuit therefore shows that designing modern electronic devices involves more than just wiring parts together to get a function. The task for the engineer is to make the best use of the relationship between physical architecture, electrical performance, power requirements, manufacturing constraints, and system goals. This further supports the main thesis of the paper, which is that electronic engineering has shifted from a more component-centered discipline to a more integrated systems-oriented discipline (Bucolo et al., 2021).

Theme 3: Embedded Systems, Sensors and the Internet of Things

Another big step in the evolution of electronic circuits to engineering systems is called an embedded system. The embedded system is a combined electronic hardware and computing and control element that carries out a certain task inside a bigger system or surroundings (Soundappan, 2022). Typically, a microcontroller is combined with sensors, communication interfaces, memory, and power-management circuits to allow devices to sense their environment, analyze data, and take action. Nowadays, the architecture is applicable to a wide range of applications from household appliances, industrial equipment, vehicles, medical devices to smart infrastructure. Since the year 2020, there have been numerous studies in print that highlight the relevance of sensors for the Internet of Things (IoT) applications. Sensors are the devices that connect the physical world to the digital world, measuring variables like temperature, pressure, movement, light, humidity, and so on, related to the environment or process they operate in. The output of the data can be utilized locally or sent to other systems for monitoring and decision-making (Kharanaq et al., 2020). This means that basic electronic circuit design principles are directly linked to wider digital systems, as the performance of the sensor relies on electronic components like signal conditioning circuits, analogue-to-digital conversion, power management, and communication interfaces. This has led to an increased role for electronic design in the integration of sensors with embedded processing. As well as determining if a circuit will be able to detect and process a signal, engineers are required to determine how efficient the entire system will be over a long period of time. Low energy consumption is especially crucial in battery powered or remotely deployed applications (Kumar et al., 2022). Circuit designers are thus required to strike a balance among processing power, energy efficiency and the need for reliable communication and sensing. The literature also shows that there are problems other than the circuit performance, which are faced by the IoT-based systems. The integration of connected electronic devices could raise issues of cyber security, privacy, interoperability and reliability

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of the system. In this context, security and data protection must also be taken into account in modern system design along with other parameters such as electrical performance, as mentioned above (Lai et al., 2025). The evolution of embedded and IoT technology is a good example of how the electronic circuit has become part of an inter-connected system as opposed to a stand-alone technical component.

Theme 4: Low-Power Electronics, Power Systems and Wide-Bandgap Semiconductors

In the modern design of electronic systems, reducing energy consumption has become a more and more critical aspect. With the growing need for portability, electric vehicles, renewable energy systems, data-processing infrastructure, and the connected sensors, there is a growing emphasis on minimizing energy loss while sustaining the performance of the systems (Sze et al., 2020). At the circuit level, this has stimulated the search for low-power architectures, effective power-management strategies, and semiconductor materials that can be turned on and off faster, at higher temperatures, and under more power-density. Silicon carbide (SiC) and gallium nitride (GaN) wide-bandgap semiconductors have been a growing research focus in recent years. For specific uses, these materials can provide characteristics conducive to higher frequency and higher temperature operation and can help to enhance power-conversion performance (Kassakian et al., 2023). The applications of the devices are increasingly relevant to the modern energy infrastructure, and the research published in 2021 has investigated smart grid and power electronic applications. These developments make more sense when looking at the shift from circuits to integrated power systems. Renewable energy conversion, electric vehicles, energy storage, industrial systems and other applications which have a critical need for efficient electrical energy conversion and control make use of power electronic circuits (Tang et al., 2021). So, depending on the semiconductor device selected, the circuit level losses can differ, as well as the size, thermal requirements, efficiency and overall architecture of the entire system. Recent reviews still point to wide and ultra-wide-bandgap technologies as next generation power electronics, but there are still difficulties with manufacturing, packaging, reliability, cost and practical system integration. This literature reveals a relationship between circuit design and the wider sustainability and energy goals. Switching devices and power-conversion circuits can improve electrical systems efficiency, but overall impact on system efficiency depends upon the system architecture, operating conditions, thermal management and application requirements. Thus, modern electrical engineers must consider semiconductor technologies as a whole system instead of analyzing the properties and characteristics of individual components only (Harris and Harris, 2021).

Theme 5: Intelligent and Edge Electronics in Modern Engineering Applications

One of the biggest advancements in electronic engineering in the modern era is bringing data processing closer to the source of data. This is correlated with edge computing and more and more smart embedded electronics. Traditional systems can send out a lot of information from sensors to cloud-based central systems for processing (Ikpe et al., 2024). Edge-based technologies, on the other hand, allow certain processing to be done nearer to the sensors and devices, which may lower communications needs and facilitate applications that demand quick response times. The evolution of intelligent edge systems has practical implications for circuit design as the hardware must be able to execute increasingly complex computational tasks while simultaneously being constrained by factors such as energy efficiency, size, cost and thermal limits (Pedroni, 2020). The incorporation of processing functions with sensors and communications technologies is the convergence of electronic, computing and artificial intelligence. Modern electronic systems can increasingly analyse on-board data and provide automated decision making instead of just gathering information. The literature on advanced electronics design also indicates that the ever-increasing complexity of the AI related hardware is also driving development of new methodologies. Within EDA, machine-learning is being explored to solve more and more complex optimisation and design challenges. In turn, AI can help in designing electronic systems, and specialized electronic circuits and processors are essential for the efficient implementation of AI applications (Chun et al., 2022). The trend towards intelligent edge electronics is especially interesting in robotics, autonomous systems, industrial automation, medical technologies, smart infrastructure, and connected vehicles. These applications entail efficient use of energy, reliable sensing, real-time processing, and low latency. The adoption of the more advanced computational intelligence, however, raises the complexity of the system and poses problems of cyber security, reliability, thermal management, hardware acceleration and software-hardware co-design. The general trend from the literature is that future electronic engineering will be more and more dominated by the integration of circuits, sensors, processors, communication technologies, and intelligent software (Pan et al., 2025). The basic concepts of circuit design continue to be as important as ever, but now they are used to help design more complex, interdependent, and more autonomous systems as a whole.

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Critical Synthesis of the Literature

The five themes clearly show a progression from the circuit-level engineering approach to an integrated, connected, energy-efficient and intelligent approach to systems. Across the literature there is a clear consensus that changes in the circuit level could have large impacts on overall system performance (Jørgensen et al., 2020). The advantages of miniaturisation are evident in the compact devices that being developed; integrated circuits are allowing more functions to be achieved; embedded systems are incorporating electronics into physical systems; and modern semiconductor technology is enhancing power conversion and efficiency. Meanwhile, smart EDA and edge-processing techniques are transforming the design and use of electronic systems. The literature also provides ample evidence of trade-offs in technological progress, however. Performance improvements can lead to greater energy usage and thermal demands, and miniaturisation can make heat dissipation and repair more challenging. As connectivity increases, so do the potential cybersecurity and privacy risks while enhancing functionality (Yang et al., 2024). Likewise, sophisticated semiconductor technologies that offer increased performance can be more complex and expensive to manufacture. Hence the move from circuits to systems should not be taken as a mere technological advance, but also as a trend toward more multi-disciplinary design and consideration of the sometimes-conflicting technical needs. A continuing research need for holistic system-level approaches also exists in the literature. Each study is typically devoted to a specific technology area such as EDA, sensors, embedded systems, or wide-bandgap semiconductors, but today's engineering applications involve the interaction of these different technologies. Future studies can therefore benefit from taking into account interaction of circuit-level innovations with system architecture, software, energy management, security, reliability and sustainability (Sazonov, 2020). This is especially relevant in the context of increasingly complex applications in electrical engineering, including smart infrastructure, electrification of transport, robotics, renewable energy and intelligent connected devices. The literature reviewed overall agrees that electronic circuit design has been and will continue to play a key role in the development of modern electrical engineering.

V. CONCLUSION

The review shows that electronic circuit design is still a cornerstone in the field of modern electrical engineering, and has evolved from simple functions of individual components to highly integrated and interconnected systems. In recent years, the development of smaller, faster, more efficient and, increasingly, more intelligent technologies has been made possible by advances in integrated circuits, electronic design automation, embedded systems, sensors and semiconductor technologies. The electronic circuits are combined with computing, communication and control technologies, which have helped in various applications in robotics, healthcare, automotive systems, consumer electronics, industrial automation and smart infrastructure. It is also noted in the literature that there is a need of a system approach in the modern electronic engineering. Energy efficiency, thermal management, reliability, scalability, security, cost and sustainability are all essential to consider with circuit performance. The field is still evolving as seen through developments in low-power electronics, wide-bandgap semiconductors, edge computing, and intelligent design techniques. However, the progress made creates complexity, production demands, cyber security and system integration challenges as well. In summary, the shift from circuits to systems is indicative of the increasing integration of electrical engineering with computing and intelligent systems. The future will rely on multidisciplinary solutions with robust circuit-level fundamentals and novel system architectures, on power technologies that are as efficient as possible and designed with a degree of intelligence, as well as on responsible engineering practices to meet the demands of increasingly connected and technologically advanced societies.

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