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Research on the Design and Application of Power Management Integrated Circuits

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ABSTRACT

With the rapid development of electronic devices toward miniaturization, low power consumption, and high integration, power management integrated circuits (PMICs), as the "energy hub" of electronic systems, have a significant impact on the energy efficiency, reliability, and battery life of end devices. This paper examines the core design and practical applications of PMICs. First, it identifies the key technical requirements for PMICs in different scenarios. It then conducts an in-depth analysis of implementation paths for topology design, energy efficiency optimization techniques, reliability protection, and electromagnetic compatibility (EMC) optimization. The feasibility of these technologies is verified by integrating mass production solutions from manufacturers such as Texas Instruments and Infineon. At the application level, this paper focuses on practical cases of PMICs in consumer electronics, new energy, industrial control, and automotive electronics. Finally, it summarizes the challenges currently faced by PMIC design, such as wide-bandgap semiconductor adaptation and high-integration heat dissipation, and looks forward to the development trend of intelligent and highly integrated PMICs. This research demonstrates that PMIC design must be guided by scenario requirements, achieving a balance between energy efficiency, reliability, and cost through the coordinated efforts of multiple technologies. Its expanded application will further promote the greener and more efficient development of the electronic information industry and the new energy sector.

KEYWORDS

Power Management Integrated Circuit (PMIC); Topology Design; Energy Efficiency Optimization; Reliability Protection; Multi-Field Applications.

1. INTRODUCTION

With the deep integration of the electronic information industry and new energy technologies, the demand for power systems in terminal devices has shifted from "basic power supply" to "intelligent regulation." Smartphones require microampere-level quiescent current to extend battery life, new energy vehicle battery management requires millivolt-level sampling accuracy to ensure safety, and industrial sensors must maintain stable output across a wide temperature range of -40°C to 85°C. Power Management Integrated Circuits (PMICs) are the core support for these demands. Traditional discrete power supply solutions suffer from large size, low efficiency, and poor consistency, making them incompatible with the current trend of "miniaturization and high energy efficiency" in electronic devices. According to data from the China Semiconductor Industry Association, the global PMIC market size will exceed US$35 billion in 2024, with demand in the consumer electronics, automotive electronics, and new energy sectors accounting for 42%, 23%, and 18%, respectively. The core driving force behind this market growth is technological breakthroughs in PMIC integration, energy efficiency, and reliability. For example, Texas Instruments' TPS62130 series PMICs leverage synchronous rectification technology to boost conversion efficiency to over 95%, while limiting quiescent current to 1.8μA. These PMICs are widely used in wearable devices. Infineon's automotive-grade PMICs are AEC-Q100 Grade 1 certified and operate stably in environments ranging from -40°C to 125°C, meeting the requirements of in-vehicle systems. However, PMIC design still faces challenges: First, requirements vary significantly across different scenarios, requiring targeted topology optimization. Second, while wide-bandgap semiconductors like GaN and SiC improve energy efficiency, they also face challenges in addressing high-frequency EMC interference and driver design. Third, high integration creates heat dissipation challenges, necessitating coordinated optimization of packaging and thermal design. Based on these challenges, this article examines the core technologies of PMIC design and, using practical case studies, analyzes the path to technology implementation, providing a reference for design optimization and application expansion. It also clarifies the core value of PMICs—not just as energy suppliers but also as a key enabler for improving terminal performance and promoting green and low-carbon development.

2. CORE DESIGN REQUIREMENTS AND TECHNICAL SPECIFICATIONS FOR POWER MANAGEMENT INTEGRATED CIRCUITS (PMICS)

PMIC design must be centered around scenario-specific requirements. Technical specification priorities vary significantly across different sectors, directly influencing topology selection, control strategies, and protection design. Core requirements fall into two categories: "basic performance" and "scenario-specific customization." Technical specifications must comply with international standards to ensure compatibility and reliability. At the fundamental performance level, conversion efficiency, quiescent current, ripple voltage, and response speed are essential. Conversion efficiency impacts energy consumption and battery life. Mainstream PMICs require over 85%. For example, the ADI ADP2114 synchronous buck topology boasts 90% efficiency at light loads and over 95% at heavy loads, complying with the IEC 62301 energy efficiency standard. Quiescent current is crucial for low-power devices in standby mode. STMicroelectronics' TLV70033 LDO offers a mere 0.5μA, sufficient for months of standby operation in smartwatches. Ripple voltage impacts the stability of sensitive circuits and is generally required to be below 50mV, achieved through RC or π-type filtering. Regarding response speed, the Texas Instruments TPS61230 utilizes peak current control, reducing response time to 2μs to accommodate dynamic processor loads. Scenario-specific customization requirements vary significantly across various sectors. Consumer electronics demand miniaturization and multi-channel functionality. The PMIC for Apple's A17 Pro utilizes a SiP package, integrating six buck converters and eight low-dropout (LDO) channels within a 10mm x 10mm footprint. It also supports USB PD 3.1, enabling fast charging and multi-device power supply. Industrial control focuses on wide operating temperatures and interference immunity. According to the IEC 60068 standard, industrial-grade PMICs must operate stably within a -40°C to 85°C temperature range and pass ESD testing. The Analog Devices ADM1085, with its hardware redundancy and EMC optimization, can achieve five years of trouble-free operation in industrial PLCs. The new energy sector demands high voltage resistance and high power density. Photovoltaic inverter PMICs must withstand DC voltages exceeding 400V. Huawei's PMICs utilize SiC MOSFETs, offering a voltage resistance of up to 650V and a power density of $2W/cm^3$, 50% higher than silicon-based solutions. Safety is particularly critical in the automotive and medical sectors. Automotive-grade PMICs must meet AEC-Q100 standards, with Grade 0 rated for -40°C to 150°C temperatures. They must also include overvoltage, overcurrent, short-circuit, and temperature protection. The Infineon AURIX-compatible PMIC, the TLE9879, relies on dual redundancy, shutting off output within 0.1ms when the power battery voltage is abnormal. Medical-grade PMICs must comply with IEC 60601, with leakage current less than 100μA. The Texas Instruments TPS7A4700, with its isolation design and certification, has been used in portable ultrasound equipment. In summary, PMIC design is characterized by "unified basic indicators, differentiated application-specific indicators." Technical specifications must be aligned with application-specific requirements and international standards to ensure optimal adaptation to end devices and stable operation [1].

3. CORE TOPOLOGY DESIGN OF POWER MANAGEMENT INTEGRATED CIRCUITS

Topology is the core of PMIC voltage conversion, and different topologies vary significantly in their principles, efficiency, and applicable scenarios. Currently, mainstream topologies include linear regulators (LDOs), buck converters, boost converters, and buck-boost converters. Resonant topologies are also gaining popularity in high-power scenarios. Topology selection must be based on input and output voltage, load current, and efficiency requirements. For example, LDO is suitable for low-ripple, low-current scenarios, Buck is suitable for high-current step-down, and Buck-Boost copes with large input voltage fluctuations. The LDO structure is the simplest, consisting of a pass transistor, an error amplifier, and a reference voltage source. Its advantages include low output ripple, fast response, and simple peripherals, making it suitable for sensitive scenarios such as RF modules. For example, the ADI ADP125, when paired with an operational amplifier, has a ripple of only 5mV and a quiescent current of 20μA; however, LDO efficiency is low. The STMicroelectronics TLV70433, through its low voltage dropout design, achieves an efficiency of over 90% in a 3.3V input, 3.0V output scenario, expanding its application range. Buck is the mainstream topology for high-current step-down. It uses a switching mode. Its core components include power MOSFETs and inductors. PWM control achieves efficient conversion, making it suitable for scenarios such as CPU power supply. Qualcomm's PM8350 buck converter, available with the Snapdragon 8 Gen3, boasts an output current of 10A and 94% efficiency at a 5A load. Texas Instruments' TPS62840 replaces traditional diodes with synchronous rectification, reducing conduction losses by 30% and increasing efficiency to 96% at a 1A load. Analog Devices' ADP2441's peak current control also allows for rapid response to load changes. Boost converters achieve voltage boost by adjusting inductor timing, making them suitable for applications such as power banks and photovoltaic inverters, with a mainstream efficiency of 92% to 94%. Infineon's IPB65R110C7 (SiC MOSFET) achieves 93.5% efficiency at 100kHz, 2.3 percentage points higher than silicon-based converters. Light loads can easily cause discontinuous mode, which increases ripple. STMicroelectronics' STCF04 uses pulse-skipping mode (PSM), achieving ripple of less than 20mV and efficiency exceeding 80% at a light load of 10mA. Buck-boost converters cope with input voltage fluctuations, and asymmetric structures are commonly used in consumer electronics due to their low cost [2]. The Dialog DA9210 boasts an input range of 2.5V to 5.5V, an output range of 1.8V to 5.0V, and an efficiency of 92% at 3.7V input and 3.3V output (1A load). The ADI AD8410 achieves ±1% cross-regulation through synchronous switching control, and its π-type filtering reduces EMC emissions by 15dB, meeting CE standards. In high-power scenarios, the LLC resonant topology achieves 96% to 98% efficiency due to its zero-voltage/current switching, reducing losses. Huawei's server power supplies use LLCs, with a 220V AC input and 12V DC output, and a 500W load efficiency of 97.5%, 3 percentage points higher than traditional buck converters. Tesla Superchargers use an LLC+buck combination, with a 380V DC input rectified by the LLC and then stepped down to 12V/24V by the buck converter, achieving an overall efficiency of 96%. In summary, PMIC topology must be closely aligned with application requirements, addressing shortcomings through control strategy optimization and device upgrades (such as SiC MOSFETs) to achieve a balance between performance, efficiency, and cost.

4. ENERGY EFFICIENCY OPTIMIZATION AND POWER CONSUMPTION CONTROL TECHNOLOGY FOR POWER MANAGEMENT INTEGRATED CIRCUITS

Energy efficiency is a core metric in PMIC design, directly impacting end-device battery life, heat dissipation, and cost. A 1% improvement in smartphone PMIC energy efficiency can extend standby time by two hours, and a 1% improvement in data center efficiency can save tens of thousands of kilowatt-hours of electricity annually. Current PMIC energy efficiency optimization focuses on reducing losses and adapting to loads [3]. Synchronous rectification, frequency adaptation, dynamic voltage scaling (DVS), and sleep mode are key technologies, already implemented in products from manufacturers such as Texas Instruments and Analog Devices, meeting standards such as DOE Level VI and EU ERP. Synchronous rectification is key to reducing conduction losses and is commonly used in buck and boost converters. Traditional diodes suffer from significant freewheeling losses, but synchronous rectification replaces them with low-resistance MOSFETs, resulting in a conduction voltage drop of only 0.05V to 0.1V, reducing losses by over 90%. For example, the Texas Instruments TPS62840 buck converter boasts an Rds(on) of only 8mΩ and 0.2W losses at a 5A load, a 94% reduction compared to diode solutions, increasing efficiency from 88% to 94%. The Analog Devices ADP2441 uses dead-band control to prevent conduction between the upper and lower transistors, thus avoiding crossover losses. Frequency adaptation balances efficiency and size by dynamically adjusting the switching frequency. Increasing the frequency under heavy loads reduces component size, while reducing the frequency under light loads reduces losses. For example, the STMicroelectronics ST1S10 buck converter increases the frequency from 200kHz to 1.2MHz when the load increases from 10mA to 1A, achieving 85% light-load efficiency and a 60% reduction in inductor size. The Infineon XE162 also supports I2C programmable frequency, adapting to different scenarios. Dynamic voltage scaling (DVS) adjusts the output voltage based on the processor's dynamic load. The Qualcomm Snapdragon 8 Gen3 PMIC (PM8350) outputs 0.7V (70mW power consumption) in standby mode, rising to 1.3V (6.5W) in gaming mode, resulting in a 15% improvement in overall energy efficiency. The Huawei HiSilicon Kirin 9000S PMIC uses dynamic voltage field-switching (DVFS) to further optimize energy efficiency. Sleep mode optimizes the PMIC's own static power consumption, making it suitable for IoT and wearable devices. The Texas Instruments TPS7A02 LDO has an Iq of 2.5μA in normal operation, dropping to 0.1μA in sleep mode, extending the standby period of a smartwatch from 7 days to 14 days. The Analog Devices ADM1085 supports external trigger wakeup with a 5μs response time, ensuring no operational interruptions. Wide-bandgap semiconductors also contribute to improved energy efficiency: GaN switches three times faster than silicon and has one-fifth the on-resistance; SiC offers a voltage withstand of 650V to 1700V. ON Semiconductor's GaN buck converter achieves 95.5% efficiency at 1MHz and 5A load, 3.5 percentage points higher than silicon-based converters. Infineon's SiC boost converter achieves 96% efficiency at 400V input and 20A load [4]. Despite the higher costs of GaN/SiC, the global GaN PMIC market is expected to exceed $2 billion in 2026. In summary, optimizing PMIC energy efficiency requires the synergy of multiple technologies and the application of wide-bandgap devices. This ensures compliance with international standards while addressing end-user pain points, which is the core competitive advantage of PMIC design.

5. RELIABILITY DESIGN AND ELECTROMAGNETIC COMPATIBILITY (EMC) OPTIMIZATION OF POWER MANAGEMENT INTEGRATED CIRCUITS

As the "energy hub" of electronic systems, the reliability of PMICs directly determines the operational stability and lifespan of end-user equipment. Failures in industrial applications can cause production line downtime, automotive electronics failures can lead to safety incidents, and medical device failures can impact patient safety. Therefore, its reliability design must address three key dimensions: fault protection, environmental adaptability, and lifespan assurance. It also addresses the EMC aspects of switching PMICs, ensuring compliance with safety standards such as IEC 61508 and AEC-Q100, as well as EMC standards such as IEC 61000-6-3. Fault protection is the primary line of defense, with hardware-based rapid protection for overvoltage, overcurrent, short circuit, and overtemperature [5]. Infineon's automotive-grade TLE9879 PMIC features an adjustable overvoltage protection (OVP) threshold and a response time of just 50ns, enabling timely shutdown of the buck converter to prevent damage to the onboard MCU. Texas Instruments' TPS62840 overcurrent protection (OCP) offers ±5% accuracy and limits current within 1μs at 12A. Analog Devices' ADP2441 short-circuit protection (SCP) utilizes cycle-by-cycle current limiting plus latching shutdown, latching after 10μs of short-circuit conditions. STMicroelectronics' STCF04 overtemperature protection (OTP) sensor offers ±5% accuracy, a 10μs response time, and protection against high-temperature aging. Environmental adaptability must address factors such as temperature, humidity, and vibration. Industrial-grade PMICs require a temperature range of -40°C to 85°C, while automotive-grade PMICs require a temperature range of -40°C to 125°C. The ADI ADR4550 bandgap reference has a temperature drift of only 2ppm/°C within this range, guaranteeing accuracy. Regarding humidity, Infineon's industrial-grade PMIC XE162, packaged in a moisture-resistant QFN, can operate continuously for 1000 hours in an 85°C/85% RH environment without degradation. Regarding vibration, Tesla's automotive PMIC uses a reinforced LGA package with an optimized PCB to meet driving stability requirements. Ensuring longevity requires optimizing device stress, heat dissipation, and packaging. Texas Instruments' TPS62130 controls the Vds stress of MOSFET to 75% of the rated value and the capacitor ripple current to 65%, with an expected life of over 10 years; Infineon's AURIX series automotive PMIC uses a PQFP package with an exposed pad, paired with a 2oz copper foil + 10 heat dissipation vias on the PCB, with a junction temperature rise of only 40°C at 10W power consumption; Huawei's server PMIC uses "SiP + ceramic substrate", the thermal conductivity of the substrate is 600 times that of FR4, and it prevents local high-temperature aging. EMC optimization requires suppressing high-frequency EMI. Texas Instruments' TPS62913 has a built-in EMI filter, reducing conducted interference by 20dB, in compliance with EN 55022 Class B standards; in the PCB layout of ADI's ADP2441, the SW node trace is less than 5mm, the power ground and signal ground are connected at a single point, and the radiated interference is reduced by 15dB; Tesla's in-vehicle PMIC uses aluminum The shielding case reduces radiated interference by 25dB, meeting CISPR 25 Class 5 standards. In summary, PMICs require multi-dimensional design collaboration and compliance with international standards to meet the stringent requirements of consumer electronics, industrial, automotive, and medical applications.

6. MULTI-FIELD APPLICATION PRACTICES AND DEVELOPMENT TRENDS OF POWER MANAGEMENT INTEGRATED CIRCUITS

Power management integrated circuits have extensive applications in the electronics, information technology, and new energy sectors. Diverging requirements in different scenarios are driving technological iterations, and technologies such as wide-bandgap semiconductors and digital control are leading PMIC development in new directions. Consumer electronics is the largest application area for PMICs (with core demands focusing on "miniaturization, low power consumption, and fast charging"). Apple's iPhone 15 series uses self-developed PMICs with integrated multi-channel converters in a package of only 10mm×10mm. It supports 27W wired fast charging and 15W wireless fast charging, with a quiescent current of less than 1μA and a standby time of up to 15 days. Huawei's Watch GT 4 is equipped with a Texas Instruments TPS7A02 LDO with a quiescent current of 0.1μA and a package of 2mm×2mm, meeting the 2-week standby requirement. Lenovo's Legion Y9000P uses Infineon's XE162 PMIC, which supports 170W fast charging and adapts to processor load through dynamic voltage regulation. The efficiency in gaming mode is 93% and in office mode is 85%. The industrial control field accounts for 23%, with "wide temperature, high reliability, and anti-interference" as the core [6]. Siemens' S7-1200 PLC uses ADI's ADM1085 PMIC, which has passed AEC-Q100 Grade 2 certification, triple protection, and continuous trouble-free operation for up to 1 million hours; the Bosch BME280 sensor is paired with an STMicroelectronics TLV70033 LDO, featuring a quiescent current of 0.5μA and a 1.2mm×1.2mm package, making it suitable for industrial battery-powered scenarios. The new energy sector is experiencing the fastest growth, requiring "high voltage resistance and high power density." Huawei's Sun2000 photovoltaic inverter uses an Infineon SiC PMIC, with an input range of 48V~800V, 96% efficiency, a power density of 2W/cm³, and a volume 50% smaller than silicon-based solutions; CATL's BMS uses the Infineon TLE9879 PMIC, which is AEC-Q100 Grade 1 certified and features a voltage sampling accuracy of ±2mV, ensuring battery safety. Automotive electronics accounts for 23% of the market, with demand shifting towards "high reliability and high integration." Tesla's Model 3 IVI system uses a self-developed SiP packaged PMIC, integrating six outputs and measuring 8mm×8mm; the Mobileye EyeQ6 chip is paired with the Infineon XE162 PMIC, certified by ISO 26262 certified, with an MTBF of 2 million hours, suitable for ADAS systems. Future PMIC development will follow four major directions: high integration, high intelligence, wide bandgap applications, and green and low-carbon development, further promoting the high-quality development of related industries.

7. CONCLUSION

This paper examines the design and application of power management integrated circuits (PMICs), covering design requirements, topologies, energy efficiency optimization, reliability and EMC design, as well as multi-domain applications and development trends, and summarizes their technical architecture and industrial value. The research shows that PMIC design must closely align with application scenarios: consumer electronics focus on a balance of "miniaturization, low power consumption, and fast charging," while the industrial sector emphasizes "wide temperature, high reliability, and anti-interference," the new energy sector demands breakthroughs in "high voltage resistance and high power density," and automotive electronics must meet "high reliability and functional safety." These diverse requirements directly influence the PMIC's topology selection, energy efficiency optimization methods, and reliability design priorities. In practical application, PMICs have established a mature path: improving energy efficiency through synchronous rectification and dynamic voltage scaling (DVS); ensuring reliability through overvoltage, overcurrent, and overtemperature protection and wide-temperature device selection; and addressing EMC issues through circuit filtering and PCB layout optimization. These technologies have been proven in mass production and comply with international standards. At the application level, PMICs are core components in consumer, industrial, new energy, and automotive electronics. For example, smartphone PMICs support fast charging, industrial PLC PMICs ensure wide-temperature stability, and new energy vehicle BMS PMICs manage battery safety, demonstrating their value in driving device performance upgrades. Current PMIC design still faces challenges: wide-bandgap semiconductors (GaN and SiC) require addressing EMC interference, driver design, and cost bottlenecks. High integration creates heat dissipation challenges, and diverse application requirements increase customization costs. Future solutions will require the development of dedicated driver chips, the use of ceramic substrates, and the promotion of platform-based design. The development of PMICs will deeply integrate the upgrading of the electronic information and new energy industries. High integration reduces costs and capacity, intelligentization enables dynamic regulation, wide bandgap applications improve efficiency, and green and low-carbon development contributes to carbon neutrality. As an "energy hub," its technological iterations will drive the upgrading of end products and contribute to the high-quality development of the electronic information industry.

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