LDO Performance and Development Trend Study

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Abstract. A low dropout linear regulator (LDO) is responsible for providing a stable supply voltage in a circuit system. Due to the characteristics of LDOs such as low power consumption, low noise, good stability, etc., it has become an essential key component of modern electronic equipment. With the continuous updating and development of electronic equipment, people have higher and higher requirements for LDOs. Therefore, the new design scheme, manufacturing process, and testing method of LDOs have become one of the hotspots in nowadays' research. To understand the current research status, development trend, and challenges of LDOs chips, this essay researches a large amount of literature, summarizes the research results of previous researchers, and explores the application prospects of LDOs in emerging technologies. The paper proposes a program that can be improved and gives an outlook on the future research direction.

Keywords: Low dropout linear regulator; low power consumption and high efficiency; wearable devices; artificial intelligence.

1. Introduction

In recent years, the development of portable electronic devices has brought more requirements in terms of practical applications. To match these developments, it is necessary to design power management circuits to control multiple voltage outputs simultaneously. A high-performance power management system can improve the efficiency of power supply energy conversion and provide a stable output voltage, thus prolonging the lifetime of electronic equipment.

Modern SOC (System-on-Chip) technology is developing rapidly. Researchers have integrated multiple circuit sub-modules onto the same chip to achieve multiple functions per unit area. However, each circuit module has different power performance requirements, so researchers must develop a variety of power management circuits to meet different application scenarios. Power management systems have become an essential part of electronic equipment systems. The charge pump power supply consists of MOS tubes with capacitors. Although the circuit principle of the charge pump power supply is relatively simple, its output voltage must be an integer multiple of the input voltage, so to get a specific output voltage needs to be combined by several charge pump power supplies. Combining several charge pump power supplies can lead to increased chip static power consumption and manufacturing costs. Therefore, charge pump power supplies lack advantages in terms of application scenarios.

Low dropout linear regulators are characterized by simple structure, low dropout, low cost, low noise, and low quiescent current. In addition, LDOs do not require large-area capacitors or inductors and are easy to integrate on-chip. LDOs offer significant advantages over charge pump power supplies. The new LDOs (Low Dropout Linear Regulators) available today have output noise as low as 30 μVRMS, PSRR (Noise Rejection Ratio) up to 60 dB, the quiescent current of only 6 μA, and even a voltage drop of only 100 mV. The new LDOs efficiently convert the voltage of a lithium-ion battery into a low voltage output of 3.3V with excellent noise rejection. Higher power energy utilization efficiency reduces losses, equivalent to providing a certain degree of protection for the battery so that the battery has a longer service life. With the rapid development of power supply technology and semiconductor processes, many researchers have discussed and optimized the performance of LDOs, such as high-power rejection ratio, low noise, and fast response.

This essay summarizes the results of previous research by reviewing a large amount of literature. It aims to understand the basic working principle of LDOs, analyze the research progress of LDOs

without off-chip capacitance, summarize the technology development trend, explore the application of LDOs in emerging technology, and make an outlook for the future research direction.

2. Basic Operating Principles of LDO

LDO is a voltage regulator device that belongs to the power management class of circuits. The basic function of an LDO is to ensure a stable output voltage within a certain input voltage variation range and load variation range. Today there are many types of LDOs, which can be classified as analog LDOs and digital LDOs according to the way they are controlled. For digital LDOs, the entire loop is controlled by digital circuits, which are mainly characterized by the ability to maintain good performance at low supply voltages, with low requirements for circuit stability. Compared to digital LDOs, analog LDOs are controlled by analog circuits. Analog LDOs have the advantages of good transient response, high power supply rejection ratio, high bandwidth, and low output noise. Analog LDOs are the most widely used LDOs. Analog LDOs are mainly composed of five basic modules such as voltage references (VREF), error amplifiers, auxiliary circuits, power tubes, and voltage feedback networks. Next, this essay will analyze the building principle of LDOs and its function in depth from the circuit structure of each module [1].

Error amplifiers have a vital role in LDOs circuits. The function of the error amplifier is to detect the feedback network acquisition signal and compare the acquired signal with the reference voltage. Finally, the operating state of the power tubes is adjusted according to the comparison results, to ensure the stability of the output voltage. In order to meet the accuracy and speed requirements of the feedback network, the error amplifier should be characterized by high gain and low output impedance. In order to meet the accuracy and speed requirements of the feedback network, the error amplifier should be characterized by high gain and low output impedance. Typically, error amplifiers are usually designed in a two-stage design, with the first stage designed to achieve the characteristic of providing high gain and the second stage designed to achieve a lower output impedance. In addition, to improve accuracy and stability, the error amplifier should also have low bias current, low bias voltage, high common-mode rejection ratio high-temperature drift stability, and sufficient bandwidth. Low bias voltage and low bias current reduce additional power consumption and increase the efficiency of the LDOs. High CMRR and temperature drift stability counteract the effects of common mode noise at the input and temperature variations on the output voltage. Sufficient bandwidth to ensure fast and accurate response to changes in the input signal. However, if the gain is too large, the loop stability design poses certain difficulties and may affect the reliability of the system, so a more comprehensive analysis should be performed when choosing the structure of the error amplifier.

LDO power tubes are MOS devices in which the output signal can be stabilized by adjusting the gate-source voltage. When designing an LDO, the designer must take into account its size and type so that the power tube can drive a wide range of load variations and achieve high efficiency. In a fully integrated LDO chip, the power tubes occupy a larger area compared to other devices. Different types and sizes of power tubes can have a significant impact on the chip's differential voltage, quiescent current, applicable power range, drive voltage, and stability. Nowadays, the types of power tubes are also more diverse, mainly including PMOS power tubes, NMOS power tubes, PNP power tubes, and NPN power tubes. The main function of the voltage feedback network is to sample the output voltage signal of the LDOs according to the ratio, and the generated feedback voltage signal is inputted into the error amplifier, which compares the feedback voltage signal with the reference voltage signal and adjusts the output voltage signal to maintain at the target value stably by accurately controlling the ratio of the feedback resistor. The main function of the reference voltage module is to provide a relatively stable voltage value under different temperature and load conditions. Researchers usually choose bandgap reference circuits to generate the reference voltage to improve the accuracy of the reference voltage.

In an LDO system, auxiliary circuits serve to enhance the performance of the LDOs and protect the chip from damage under extreme conditions. Commonly used auxiliary circuits include start-up

circuits, current limiting circuits, undervoltage protection circuits, and over-temperature protection circuits. The following section describes the function of each auxiliary circuit in turn. The function of the startup circuit module is to ensure that when the chip is powered up, all the functional modules of the LDOs are out of the zero operating point so that the LDOs can eventually produce the appropriate output voltage. When designing the startup circuit, the designer needs to pay attention to the speed of the startup, the overshoot voltage, and the power consumption of the timing chip after normal operation.

The purpose of the current limiting circuit module is to prevent the LDOs chip from supplying too much current to the outside world and thus causing the chip itself to burn out. The current limit circuit continuously detects the size of the LDOs output current value, compares it with the threshold value, and controls the negative feedback loop to turn on after the output current reaches the threshold value. The current limit circuit module limits the current flowing through the power tube by controlling the gate terminal voltage of the power tube, forming a new loop to stabilize the output current of the LDOs. The current limiting circuit ensures that the load current remains within the normal operating range by the above means, realizing the role of current limiting, and ultimately ensuring that the transistors inside the chip do not break down.

The purpose of the undervoltage protection circuit module is to protect the LDOs from damage caused by the chip when the output voltage is lower than the specified value, and to ensure that the LDO is able to obtain enough input voltage to maintain the stability of the output voltage during operation. When the input voltage falls below the preset threshold, the undervoltage protection circuit sends out a control signal to shut down the chip prematurely. On the contrary, the undervoltage protection circuit will automatically activate the chip and return the system to its original operating state when the input voltage exceeds a preset threshold.

The purpose of the over-temperature protection circuit module is to prevent the chip temperature from being too high or too low and damaging the device. High or low temperatures can lead to changes in the operating state of the device, some of which are even irreversible. Higher temperatures increase the power consumption of the power tubes, leading to degradation of the LDO 's performance. Normally designers will design a temperature sensor inside the LDOs chip. When the temperature exceeds the threshold, the over-temperature protection circuit generates a signal to shut down the circuit. When the internal temperature of the chip is below the threshold, the over-temperature protection circuit then restores the normal operation of the LDOs. The over-temperature protection circuit can effectively monitor the internal temperature, thus ensuring the normal operation of the LDOs and improving the stability and accuracy of the LDOs.

3. Trends in LDO

3.1. Emerging Technologies and Applications

With the informationization, digitalization, and intelligence of human society accelerating, all kinds of electronic equipment, which are widely used in human production and life, are developing in the direction of high gain, high precision, and high reliability. Semiconductor chips, as the core of electronic devices, are increasingly demanded by researchers. In this paper, by summarizing a large amount of literature and research results, nowadays LDOs are found to be used in application scenarios mainly focused on the industrial field, wearable devices, flexible electronics, and the medical field, etc. The research hotspots of LDOs are mainly for low power consumption and high efficiency, temperature stability and reliability, and the reduction of the size of the integration degree. [2]. In the industrial sector, the demand for automated processes in industrial production and automotive electronics has been increasing since the post-Singapore epidemic era. These areas require the assistance of many measuring and testing electronic devices. In these application scenarios, power supplies often provide 12V or higher high voltages, so scenarios such as industrial and automotive electronics often utilize direct access to high-voltage LDOs. For example, TI (Texas Instruments), Renesas + Intersil (Renesas Electronics), Maxim (Maxim), and other large companies have invested

heavily in the direction of high-voltage LDOs. Multiple types and multi-functions of high-voltage resistant LDOs products are being introduced by large companies. In addition, for industrial production and automotive electronics, low power consumption is also a major research direction. Low power consumption is conducive to the extension of battery life and the miniaturization and lightweighting of electronic devices, which can reduce the heat generation of the LDOs chip and enhance system safety and stability [1].

In the field of flexible electronics and medicine, with the continuous progress of science and technology and the continuous improvement of medical standards, medical equipment has made great breakthroughs. Implantable medical devices (e.g., brain implantable stimulators, artificial retinas, cardiac pacemakers, etc.) are now widely used in clinical practice to assist the human body in accomplishing various functions. For such an implantable human communication chip, the LDO is an indispensable module. Due to the special characteristics of in vivo implantation, the LDOs chip size should be small enough to have low power consumption and strong anti-interference ability, while the heat and radiation should meet the human body safety standards [2].

In addition to implantable medical devices, the number of people suffering from age-related chronic diseases (e.g., cardiovascular disease, type II diabetes, etc.) is increasing as the global population grows and ages. The demand for healthcare resources is increasing, while the current state of healthcare resources globally is not encouraging [3]. The emerging field of mHealth has received widespread attention, with wearable devices becoming the ideal terminal for daily health monitoring. Wearable flexible sensors usually have the advantages of high flexibility and high biocompatibility, which can monitor human vital signs in real-time and help people to better detect health status and find problems in time [4]. Because of the portability of wearable devices, non-invasive testing is becoming increasingly popular with the public. Huawei and Apple launched the HUAWEI WATCH series and Apple Watch series smartwatches. Smartwatches can intelligently detect people's sleep status, blood oxygen levels, heart rate, and other information, and send warning alerts when they detect that the body's functions are in an abnormal state. Apart from Apple and Huawei, other tech giants like Google, Sony, and Xiaomi are also actively participating in the competition in the field of wearable biomedical devices. To enable biomedical chips to perform optimally when processing weak physiological electrical signals and to ensure the accuracy of processing bioelectrical signals, LDOs need to have high power supply ripple rejection characteristics within the bandwidth of bioelectrical signals [5]. The continuous research, optimization, and breakthroughs of LDO chips are of great significance for applications in the medical field, biomonitoring, and human-computer interaction.

In the field of wearable devices, with the development of intelligent electronic devices and the improvement of people's living needs, wearable electronic devices are widely used in various fields of daily life. For example, Bluetooth headphones have become a favored everyday item. Due to the limitation of the battery capacity, people have higher and higher requirements for the endurance of electronic devices, so low power consumption has become a hot spot in current research. LDOs, as an indispensable and important part of electronic devices, whose power consumption will directly affect the endurance of the device. By optimizing the existing techniques, researchers have met the requirements of LDOs for low power consumption, high accuracy, high stability, and high transient response in modern consumer electronic systems. The trend of intelligent portable wearable devices has driven the research on low-power LDO chips [6].

3.2. Difficulties and challenges

Low dropout linear regulators (LDOs) are important and widely used in electronics, but LDOs are still facing some challenges in the current technological development process. China's 40th Antarctic research expedition is currently underway. The expedition requires the monitoring of climate, and biological activities through a variety of self-instrumentation, sensors, and electronic devices. Devices all need a reliable power supply, so LDO plays a vital role. Extremely harsh weather conditions in Antarctica are undoubtedly a test for electronic equipment. How to maintain the stability

and reliability of LDOs under extremely low-temperature conditions is a major challenge. At the same time, power supply in Antarctica faces energy constraints. Conventional LDOs generate large static power consumption. How researchers can minimize the quiescent current power consumption of the LDO chip while maintaining the normal operation of the chip and ensuring that the LDO has a good transient response is also a major difficulty.

Nowadays artificial intelligence is a major research hotspot around the world, and LDOs are widely used in processors, sensors, and embedded systems. Artificial intelligence systems have stringent requirements for LDO power consumption, efficiency, and system stability. Conventional LDOs generate large static power consumption and heat, affecting battery life and system performance. Artificial intelligence requires high signal quality and accuracy, so it is a challenge for researchers to design LDOs with good noise rejection ratios and power supply rejection ratios.

With the progress of integrated circuit technology and design level, researchers how to design a smaller size and better performance of the LDO for the everlasting topic. As the size shrinks to deep submicron and nanoscale processes, researchers find that the problems of device interference and interconnect crosstalk become more pronounced. Therefore, how to improve the immunity of the circuit is an issue that designers need to seriously consider. Designers need to find the most suitable circuit structure according to the needs of different systems reasonably optimize the various performance indexes according to the demand, and finally get the suitable circuit [7].

3.3. Development Proposals

Researchers can seek a technological breakthrough with advanced CMOS processes. For example, researchers can use an improved FinFET process to increase the control of control gates and improve the performance and power efficiency of LDOs by forming thin wings (Fin) around the transistor channels. Many scholars have improved the circuit by optimizing the feedback network and circuit topology to achieve the low power consumption of LDOs. For the problem of LDO system stability, researchers can try to realize it using Miller compensation. At extremely low temperatures, such as the South Pole, the designer can design a bandgap reference circuit with a segmented compensated low-temperature drift coefficient, which ultimately outputs a low temperature-drift segmented compensated bandgap reference voltage as a way to improve the accuracy of the LDO output voltage. With the general trend of development in today's chip industry, LDO chips are becoming more and more integrated. Researchers also need to consider the problem of reducing mutual interference between components when solving the size problem and finding the most suitable circuit structure. In conclusion, low power consumption and high efficiency, noise rejection ratio and power supply rejection ratio, temperature stability and stability, integration, and size reduction are the research hotspots of today's LDOs. Researchers can continue to break through the research by way of circuit improvement and optimization, eventually realizing an LDO that combines many advantages.

4. Conclusion

By analyzing the working principle of LDO, this essay concludes that the research trends of LDO are low power consumption and high efficiency, improvement of temperature stability and reliability, and reduction of integration size. The two aspects of performance, low power consumption, and high efficiency have always been the research hotspots of LDOs. Researchers have been working to improve the overall efficiency of LDOs and reduce power consumption. In addition to this, the effect of small poles caused by low quiescent currents on the stability of LDOs is also a major challenge. Researchers have worked on the improvement of noise rejection ratio and power supply rejection ratio as a way to ensure the stability and accuracy of LDOs and improve the performance of LDO circuits. The ability of a power management chip to handle a wider range of inputs is an important performance indicator. The researchers worked to solve the problem of poor circuit stability and slow response based on wide-input circuit design. Performance stability at different temperatures is critical for electronic devices. Researchers are working to improve the system stability of LDOs in extreme

temperature situations and are investigating new materials and processes to improve the reliability and lifetime of LDOs. With the trend toward portability of electronic devices, the need for integration of LDOs is increasing, and researchers are working to develop new integration techniques to achieve higher levels of integration and smaller chip sizes to meet the needs of compact devices.

In addition, this essay analyzes today's application scenarios of LDOs in the industrial field, medical field, etc., and suggests that LDOs are still facing many challenges in the field of artificial intelligence and extreme weather conditions at present. For example, how to reasonably optimize the various performance indicators as needed, reduce power consumption, and improve accuracy and stability to get the most suitable circuit. In the last part of this paper, improvement suggestions are given. This paper only summarizes the previous research results, based on which the LDO application scenarios and development trends are analyzed, and there is no practical solution to the problems and challenges. In the future, researchers can further go through the practice to overcome the challenges and solve the current difficulties encountered.

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