Topology Optimization Design of Rectifier in Microgrid Scenario

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Abstract. With the increase of renewable energy penetration and the rapid development of AC-DC hybrid microgrid, the performance of rectifier circuit, as the core device to realize the efficient coupling of AC source and DC bus, directly affects the power quality and operation efficiency of the system. Traditional rectifiers face challenges in dealing with new energy volatility, harmonic suppression and multi-operating condition adaptability. Most of the research on the market focuses on emerging topologies such as three-phase rectifiers and matrix rectifiers. The main methods are to improve stability and improve efficiency in the power grid by changing the component materials and the direction of computers such as virtual synchro. The above methods are not widely used in complex power grids and microgrids. The purpose is to develop an intelligent rectifier system with high power density and low harmonic distortion, achieve wide-range impedance adaptation of the power grid through multi-mode collaborative control, build an energy efficiency optimization model with an efficiency which is Sufficient for daily use， This paper aims to provide a power topology of single-phase rectifier under the new microgrid condition, by using the nmos and pmos to replace the diode in the original circuit.

Keywords: Microgrid, Topology Optimization, Rectifier, Circuit Design

1 Introduction

With the gradual depletion of energy resources such as oil and coal mines, photovoltaic and wind power are becoming explosively increasing. Renewable energy sources such as power generation and fuel cells are becoming increasingly common applications [1]. The output power of renewable energy is subject to intermittent and random effects from environmental factors, load, current, and other factors, which may lead to significant power fluctuations, especially in independent new energy supply systems. Therefore, to reduce the impact of power fluctuations on DC or AC distribution busbars, energy storage devices such as batteries and supercapacitors are usually needed to ensure the continuity and stability of the power supply [2]. The concept of microgrids is becoming increasingly popular, and the current situation of microgrids is very different from the past. Microgrids have developed rapidly in recent years, and the

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market size has reached billions of dollars, with advanced technology in North America and Europe dominating. The Asia Pacific region has become the fastest-growing region due to energy demand and power grid evolution. Unlike the past microgrids, the global technological level has advanced and there have been breakthroughs in energy storage technology. The intelligent management approach and integration of distributed energy have made microgrids widely welcomed around the world. In the process of progress, microgrids have also encountered many core problems, such as cost constraints, insufficient technical compatibility, that is, inadequate compatibility of equipment and stability of some equipment. At the technical level, power quality should be improved. At the economic level, the government should optimize costs, provide subsidies and incentives through policies, and determine the most reasonable grid laying method through digitalization and intelligent algorithms

At the same time, in the field of energy, some microgrids cannot carry renewable energy, and the intermittency of photovoltaic and wind power has brought great challenges to microgrids. At the same time, there are also minor problems in other aspects, such as imperfect government policies and regulations, and high complexity of operation and management. The core method of traditional rectifier topology research is to establish the state equation of the rectifier by mathematical modeling and theoretical analysis, and to obtain the change of guideline factor by analyzing the relationship between output and input voltage and harmonic content. Finally, the efficiency is calculated, and if the efficiency is improved, a new circuit topology can be obtained after further simulation and optimization. From the perspective of research direction, the research direction of traditional rectifier topology is generally harmonic suppression and power factor correction, or efficiency improvement and loss optimization, or the expansion and application of multi-store topology, and the most popular research direction recently is the digital control and intelligence of the entire topology. There are limitations to the traditional rectifier topology research. The uncontrolled/semi-controlled rectifier has harmonic pollution, low power factor, high cost and large components. In this paper, integrated design is added to the traditional research direction, and green changes are made, so that the rectifier topology can cope with more complex output devices. The traditional bridge rectifier is combined with the analog circuit direction, and an optimized topology scheme is proposed, which solves the problem of high cost and inflexiability of the traditional rectifier topology [3].

2 System Architecture and Rectifier Topology Design

2.1 Typical Structure of Microgrid

The typical structure of microgrid is mainly composed of distributed power supply, energy storage system, load, control management system and grid-connected interface: 1. Distributed power: Includes renewable or clean energy sources, such as photovoltaic, wind power, gas turbines, as the main power source. Energy storage system: lithium battery, supercapacitor, or flywheel energy storage, smooth power fluctuations, to achieve energy time shift. Load: Covers industrial, commercial, or residential electrical equipment that can be adjusted to match the balance of supply and demand. Control system: Based on energy management (EMS) and power electronics converters, coordinates the operation of energy storage loads and supports seamless switching of grid-connected/island modes. Grid-connected interface: Connected to the main grid via PCC (common connection point), equipped with protection to ensure quick disconnection in case of failure. The microgrid structure presents the characteristics of modular and hierarchical control, which can be flexibly expanded according to the requirements of the scene, and realize efficient and autonomous operation through intelligent algorithms (such as multi-agent systems). Its core objective is to maximize renewable energy penetration while ensuring the reliability of the power supply.

For multi-port control, it is required that the efficiency after adopting multi-port control should at least double. Meanwhile, according to the requirements, the harmonic magnitude of the circuit topology should be less than 5% of the fundamental wave.

2.2 Multi-port Rectifier Requirement

The background of the demand is the multi-energy integration demand, and the multi-port design can reduce the number of devices and reduce the complexity of the system. It also requires space and cost optimization, mainly reflected in reducing volume and hardware costs, which is suitable for space-constrained scenarios. The multi-port design can also ensure the bidirectional flow of energy, supporting the operation of power to storage, storage to load, and also support the reverse. The core demand of multi-port converters is to achieve efficient, reliable and compact integration of multi-energy sources through structural innovation and intelligent control, which will accelerate the development of high-frequency, intelligent and standardized direction in the future.

2.3 Circuit Design

According to the most basic rectifier circuit topology design, that is; single-phase bridge rectifier can be seen in textbooks or basic textbooks. The advantages of this single-phase bridge rectifier are a simple structure, only four diodes, low cost, and relatively high reliability. As a full-wave rectifier, the output ripple is small, and the control circuit is not required to run.

However, there are many disadvantages, the single-phase bridge rectifier circuit output harmonic is too large, the power factor is very low, which will have an impact on the entire power grid. There are other disadvantages, such as the output voltage is not adjustable, cannot access a variety of power grids, and can only access a certain limit within the circuit transmission network. The biggest problem is that the diode component in high voltage, high current, high frequency, high temperature and other special or in the actual application will meet the environment cannot operate normally or the life of the component will be rapidly reduced because of the special environment, if the actual use of diode components, whether from the cost or in the safety and overall reliability is unreasonable.

It is a reasonable and important direction to optimize the performance of the whole rectifier by adjusting the components of the circuit itself from the perspective of a single-phase basic circuit topology without considering the three-phase operation of the power grid. Due to the progress of microgrid and the change of operation mode, it is easy to infer the connection between the traditional rectifier corresponding to microgrid operation and the analog circuit components. Analog circuit components are generally simple, high efficiency, small size, low power consumption and high reliability, which can effectively make up for the shortcomings of diode components, so that the entire circuit topology is stable and durable, and the service life is extended. Reduce the number of unnecessary components and adapt to more complex input and output environments, and the working environment of the entire circuit.

For the circuit topology selected for the experiment, the circuit was initially improved based on the simplest and most traditional single-phase semi-controlled bridge rectifier circuit topology [4]. The core component is the diode. Due to the advantages and disadvantages of the diode component itself mentioned earlier, when the input voltage is constant, its rectification effect decreases with the change of the load. Until the load changes to the point where the output voltage will break down the diode. According to the experimental results, under the condition of resistive load, when the control capacitor connected in parallel on the output side is constant and the load is within the daily usage range, it will also cause diode. According to the experimental results, under the condition of resistive load, when the control capacitor connected in parallel on the output side is constant and the load is within the daily usage range, it will also cause diode breakdown when it reaches a certain value, that is, resulting in equipment damage. And the initially selected circuit is like Fig. 1 [5].

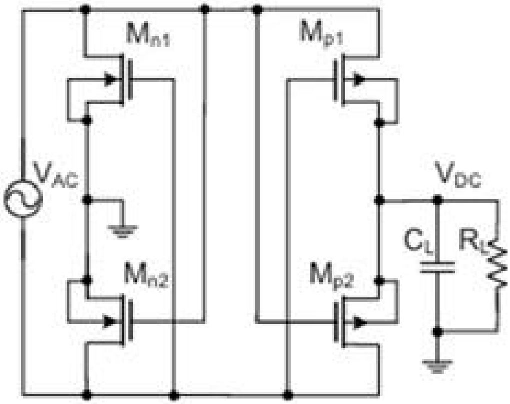

Fig. 1. Initial design

From the perspective of the design of multi-port bidirectional rectifiers, the goal of the multi-port control strategy is to optimize dynamic response, efficiency, and reliability. In this paper, several methods are adopted to optimize the circuit topology. On the one hand, distributed drive control is carried out, dividing the control circuit into two parts. Through timing interlacing, efforts are made to ensure the stability of both positive and negative waveforms. On the other hand, by adopting multi-port coordination, multiple control buses are used to coordinate the duty cycle of each MOSFET, respectively.

The low on-resistance of the new MOS tube means that less energy is lost when the current passes through the device when it is powered on [6], which is crucial for rectifiers, power management and power conversion systems, because the reduction in power loss will directly improve the overall efficiency of the system [7]. For example, in the automotive rectifier, the low on-resistance of the MOS tube can reduce the power consumption of the rectifier at work, reduce the generation of heat, help to improve the efficiency of the rectifier, reduce the dependence on the cooling system, and improve the reliability and stability of the rectifier [8]. Traditional MOSFETs usually produce higher switching losses during the switching process, while the new MOS tube switches faster, and the on-off and off-off time is shortened, which reduces the overlap of current and voltage during the switching process [9]. This effect of reducing switching losses directly improves the efficiency of power conversion. For example, in high-frequency switching applications, in electric vehicle drives and power converters, the new MOS tubes can quickly switch currents, reducing energy losses and improving overall efficiency.

The replacement structure of only one pair of diodes and MOS switches avoids this problem, as the remaining diode pairs do not conduct in reverse like the switches here (except for small leakage currents). However, this structure will be affected by higher voltage drops from other diodes.

The second step is to combine the traditional buck chopper circuit topology [10]. Under the condition of using a traditional rectifier, the chopper circuit is combined. The experiment aims to determine whether the semi-controlled bridge rectifier circuit can operate normally in some working environments that slightly exceed the rated voltage of its components under the control of the output [11]. However, according to the simulation, it is found that chopping can still only control the output size and has no effect on the rectifier in the first stage. The output waveform still does not meet the requirements.

When the first two attempts failed, the single-phase traditional semi-controlled bridge rectifier circuit could no longer be updated. Therefore, attempts were made to replace the diode with other components, combining analog and digital circuit components. The MOSFET became the target component to replace the diode. Because of its fast-switching speed and high frequency, it is initially thought to be suitable for use in rectifier circuits, which can effectively combine with high frequency input voltage, while the MOSFET itself has high input impedance and voltage control characteristics, low power consumption but high efficiency, also has high heat resistance and high reliability, flexible application scenarios and low noise. The most important point for choosing MOSFETs is that their structure can effectively suppress harmonic components and reduce the interference of harmonics.

Another major advantage of using MOSFET components is that they can be easily combined with PWM control systems in circuits, that is, pulse width modulation. Pulse width modulation is an analog control method that modulates the bias of the transistor base or MOSFET gate according to the change of the corresponding load to achieve the change of the conduction time of the transistor or MOSFET [12], thereby changing the output of the switching regulated power supply. This method can keep the output voltage of the power supply constant when the working conditions change. It is a very effective technique for controlling analog circuits by using digital signals from microprocessors. It is widely applied in many fields, ranging from measurement and communication to power control and conversion. Due to the limitations of the software used in the experiment, the PWM system cannot be constructed in the LTspice software [13]. However, on the whole, it is a highly likely optimized circuit topology expansion for the single-phase bridge rectifier circuit with MOSFETs as the main components.

3 Simulation Results and Comparative Verification

The objective of the simulation design experiment is to design a brand-new single-phase bridge rectifier circuit topology based on the pre-designed circuit. For the parameter design, a load that might be encountered in daily life but would cause the diode to break down in the laboratory was adopted [14]. That is a resistive inductive load of a 10 Ω resistor and a 10mH inductor. The font size of MOSFET is 1.5. If the microgrid inverter adopts a fixed duty cycle, it will be unable to cope with the power fluctuations caused by sudden load changes. Therefore, a stable sinusoidal input voltage is used as the input to reduce the control complexity of the circuit and lower the frequency of harmonics [15].

Based on the above and design experience, this paper adopted the circuit design as shown in Fig. 2, and obtained the simulation results as shown in Fig. 3.

Efficiency calculation formula: $\eta = Wt/Wi$. According to the data in Figure 3, it can be concluded that $\eta \approx 100V/10V = 10$, which meets at least twice the requirements of the experiment.

In addition, there are requirements for harmonics, which should not exceed five percent of the fundamental wave.The equation for the Fourier expansion of harmonic components is:

$$x(t) = a_0 + \sum_{n=1}^{\infty} a_n cos(2\pi n f t) + b_n sin(2\pi n f t) \quad (1)$$

Where a_0 is the fundamental wave content, n is the harmonic order

The calculation formula for the third component with the largest harmonic is

$$x_3(t) = a_3 \cos(6\pi f t)\, b_3 \sin(6\pi f t) \quad (2)$$

$$A_3 = \sqrt{a_3^2 + b_3^2} \quad (3)$$

A_3 is the amplitude of the third harmonic. According to the FFT image (Fig.4), it can be seen that the relationship between the fundamental wave and the third harmonic is twice, which is 10 to the power of 2 in the time domain. So the third harmonic component is approximately 1% of the fundamental wave, so it satisfies the amplitude of the third harmonic component <5%

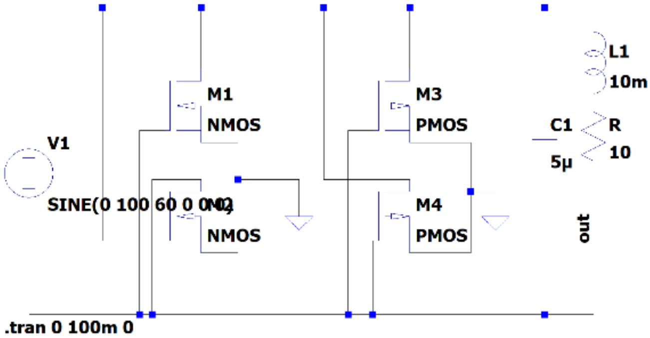

Fig. 2. Optimized circuit

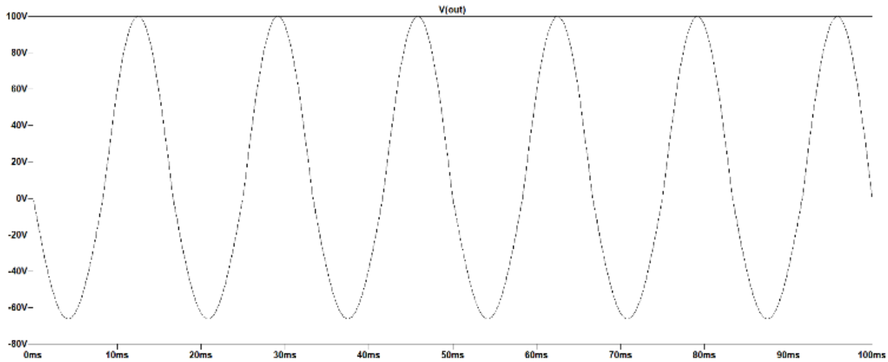

Fig. 3. The output waveform of the optimized circuit

It can be seen from the FFT image (Fig. 4) that the output of the new circuit topology is stable and meets the requirements. It achieves stability with small harmonic components and has an optimization effect compared to the waveforms of traditional circuits.

Under the same load and the same input voltage, the output waveform of the traditional single-phase semi-controlled rectifier circuit is not sinusoidal at all, that is, the rectification has no effect or even has the opposite effect. This further demonstrates the necessity and correctness of this simulation. The circuit topology of the basic single-phase semi-controlled rectifier circuit is shown in Fig. 5, and the output waveform is shown in Fig. 6.

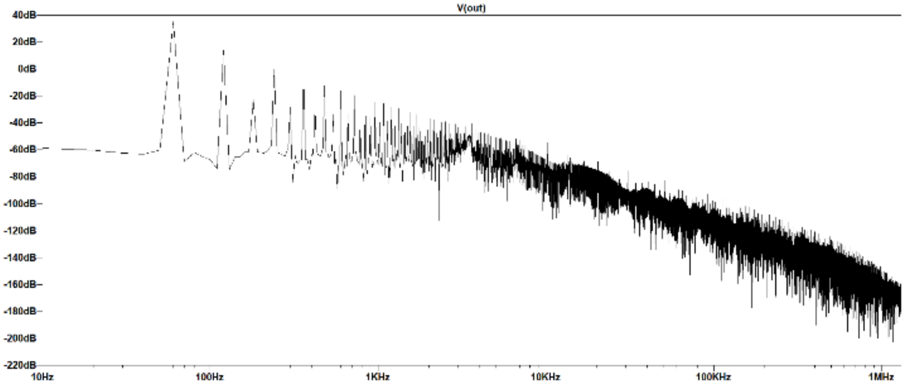

Fig. 4. FFT image

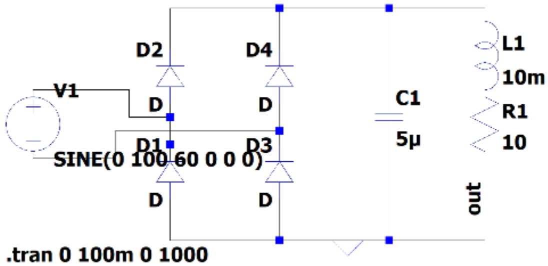

Fig. 5. the traditional power topology with the same parameters

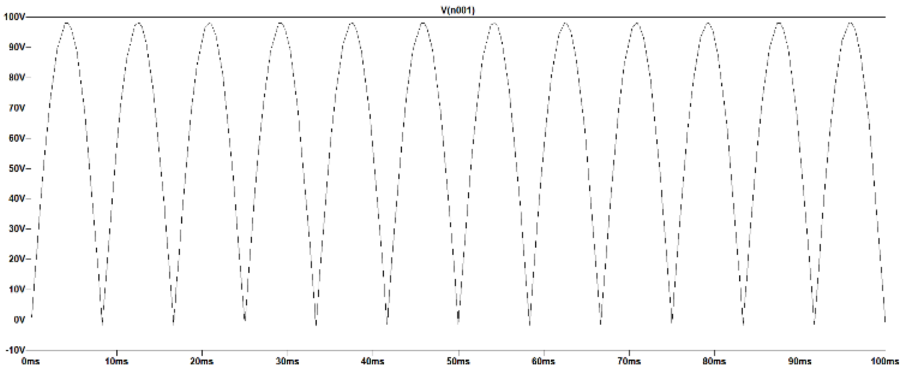

Fig. 6. The output voltage of the traditional power topology with the same parameters

4 Conclusion

Based on the design requirements, this paper selects the appropriate circuit structure. A brand-new power topology was designed on the basis of the basic circuit topology.

MOSFETS were used to replace the traditional diodes, and the wiring mode of the circuit was changed at the same time. After conducting simulation experiments, it was proved that the optimization was feasible, and there were improvements in both cost and equipment stability.

Finally, the optimization results were obtained through comparative experiments. By comparing the output waveforms and FFT images, it was indicated that the simulation experiments were successful. The new circuit topology can meet the requirements, but there is still room for optimization.

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