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Analysis and Design of a Single Phase Full Wave Rectifier Circuit with R-L Load in a Split Supply System: Efficiency Evaluation and Voltage Stabilization Approach

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Abstract

Integration of various systems with the utility network can be done through electrical energy conversion using power electronics. Power electronics converters function to condition and process electrical energy to meet end user needs. In an off-line converter system, the utility network with a frequency of 50/60 Hz becomes the input side, while the output properties of the converter are determined by several parameters such as voltage, frequency and number of phases. Power electronics converters generally consist of several important components, such as terminating semiconductor devices (such as IGBTs, MOSFETs, and diodes), inductors, generators that function as energy storage or conversion devices, heatsinks for cooling, and power transformers for isolation. In this study, we discuss an uncontrolled single-phase full-wave rectifier, which uses two diodes. The analysis results show that this rectifier produces a smaller peak-average voltage compared to the half-wave rectifier, and has lower ripple due to the use of two diodes in the energy conversion process.

Keywords: Power electronics, energy conversion, rectifier systems.

1. Introduction

In modern power systems, the integration of various electronic devices with utility grids has become increasingly feasible, primarily due to advancements in power electronics and their ability to efficiently convert electrical energy (Kwasinski and Onwuchekwa, 2011). Power electronics converters play a pivotal role in this process by conditioning and processing electrical energy to meet specific needs of the end user, thereby enhancing the overall efficiency of the electrical distribution system (Emadi and Ehsani, 2001). These converters typically operate in off-line configurations, where the utility grid, which operates at standard frequencies of 50/60 Hz, serves as the input source for the power electronic devices (Emadi et al., 2006).

The design of a power electronics converter is governed by several key output requirements, such as the desired voltage, frequency, phase number, and current stability (Kwasinski and Krein, 2007). For a system to function effectively and reliably within the utility grid, these parameters must be met with precision. As part of the converter's internal structure, several critical components are utilized to ensure efficient performance. These components often include semiconductor switching devices (such as IGBTs, MOSFETs, and diodes), which are responsible for regulating the flow of electrical current; inductors and capacitors, which serve as energy storage elements or filters; heatsinks for maintaining optimal thermal conditions and preventing overheating; and power transformers to provide electrical isolation between the grid and the load (Shiddiq et al., 2022).

Additionally, the conversion process in these systems is particularly relevant when considering full-wave rectifier circuits, especially in configurations with R-L loads (Basak and Parui, 2008). This setup is frequently used in systems that require efficient conversion of AC to DC power, such as electrical vehicles, industrial machinery, and renewable energy systems. The design of such rectifier circuits in split supply systems is complex, as it involves balancing voltage stabilization, efficiency, and power factor correction to ensure that the end-user receives consistent and reliable power.

The evaluation of efficiency and the enhancement of voltage stability in these systems are critical to their performance (Xu and Cheng, 2008). Achieving high efficiency ensures minimal energy losses during conversion, while voltage stabilization is necessary for protecting sensitive equipment connected to the grid. Both these factors are essential for improving the reliability and sustainability of modern power systems, especially in contexts where renewable energy integration is a key concern.

2. Material and methods

2.1. Methods

A full-wave rectifier is an advanced rectification system that utilizes two complementary diode blocks, where each block typically consists of diodes arranged in parallel or series configurations to rectify both halves of the AC input cycle (Onwuchekwa and Kwasinski, 2007). During operation, one diode conducts during the positive half-cycle of the AC input, while the complementary diode blocks operate during the negative cycle.

DOI xxxxxx

This configuration enables the rectifier to process both cycles of the AC waveform, effectively doubling the frequency of the output signal when compared to a half-wave rectifier (Onwuchekwa and Kwasinski, 2011).

In the context of power electronics, a full-wave rectifier is often implemented using a center-tapped transformer (CT), which provides two AC output signals with opposite phases (Rivetta et al., 2005). The key advantage of this configuration is that it ensures a smoother DC output by utilizing both halves of the AC waveform, reducing the ripple content when compared to half-wave rectification. As a result, the output waveform from a full-wave rectifier is more continuous, although it still contains periodic fluctuations at the ripple frequency (Bintari et al., 2022).

It is crucial to note that while the full-wave rectifier provides higher average DC voltage than a half-wave rectifier, it does not entirely eliminate the ripple. The voltage waveform exhibits a series of peaks and valleys, resulting from the rectifier's ability to switch between positive and negative cycles. This characteristic is particularly relevant in engineering applications where voltage stabilization is important, especially in systems with R-L loads. Such loads, which combine resistive and inductive elements, often require careful voltage regulation to ensure that the voltage supplied to the load is stable and within the desired range (Karimipour and Salmasi, 2014).

In practice, the rectifier's efficiency is closely linked to the phase shift between the AC input signal and the DC output. The smoother the rectified signal, the more efficient the power delivery becomes, reducing energy losses and improving system performance (European Control Conference et al., 1999). Therefore, the full-wave rectifier is widely employed in various power conversion applications, such as DC motor drives, solar power systems, and battery charging systems, where efficiency and voltage stabilization are critical.

2.2. Material

2.2.1. Diode

A diode is a fundamental semiconductor device that acts as a unidirectional switch, allowing electric current to flow in one direction while preventing flow in the reverse direction (Fauzi et al., 2024). This characteristic makes the diode an essential component in power electronics systems, particularly in rectifiers, where it plays a key role in converting alternating current (AC) to direct current (DC). As a rectifying element, diodes are widely utilized in AC to DC conversion circuits, such as single-phase and three-phase rectifiers, which are central to many power supply systems and electronic devices (Rahman et al., 2024).

The forward biasing of the diode occurs when a positive voltage is applied to the anode (positive lead) relative to the cathode (negative lead). In this condition, the diode conducts current, allowing it to pass freely through the junction. When reverse biased, the diode acts as an insulator, effectively blocking the flow of current, which is crucial for ensuring that current only flows in one direction and preventing reverse current flow in rectification processes. The diode's characteristics, such as its voltage and current ratings, determine its suitability for different applications, including those in power rectifiers that supply resistive-inductive (R-L) loads.

In the context of the single-phase full-wave rectifier circuit, the diodes are arranged in specific configurations to maximize the efficiency of the rectification process. These arrangements, often involving multiple diodes in parallel or series, ensure that both the positive and negative halves of the AC input signal contribute to the DC output, resulting in a more efficient conversion and smoother waveform. However, during reverse bias, the diodes in a rectifier configuration block the current flow, thus ensuring the proper functioning of the system by only allowing current to flow in the intended direction.

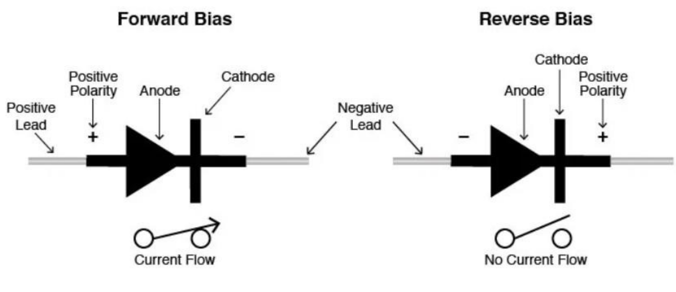

Figure 1. Diode symbol

When using tools like a digital multimeter to test a diode, a small voltage is applied across the test leads (Mu'in et al., 2023). This voltage is sufficient to forward bias the diode, and the meter will

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display a voltage drop typically between 0.5 to 0.8 volts for a properly functioning diode. The forward bias resistance of a healthy diode is usually in the range of 1000 to 10 ohms. In contrast, when the diode is reverse biased, the multimeter will show an open loop (OL) indication, which reflects the very high resistance characteristic of the diode in this state. These testing procedures are critical for ensuring the reliability and integrity of the diodes used in rectifier circuits, particularly in systems where voltage stabilization and high efficiency are crucial for performance.

In the analysis and design of a single-phase full-wave rectifier circuit with R-L loads, such characteristics of diodes are pivotal for achieving a stable DC output with minimal ripple (Amrullah et al., 2023). The voltage stabilization achieved through these circuits is essential in various engineering applications such as renewable energy systems, battery charging systems, and industrial power supplies, where precise control of the output voltage is required to protect sensitive equipment and ensure consistent operation.

A. Diode as Rectifier

In the design and analysis of rectifier circuits, the diode plays an indispensable role as the key component in controlling the flow of electrical current. A diode is a semiconductor device that allows current to flow in only one direction, thereby providing rectification (Nugraha et al., 2023). This unidirectional conductivity is essential for converting alternating current (AC) into direct current (DC), making diodes the cornerstone of power electronics in a variety of applications ranging from power supplies to signal processing systems.

Historically, the concept of the diode was first introduced by Ambrose Fleming, who referred to his invention as a "valve" due to its ability to regulate the flow of electricity in a single direction. Today, semiconductor diodes, which serve the same purpose as Fleming's original design, have evolved into more compact and cost-effective components (Erickson and Maksimovic, 2001). Modern semiconductor diodes now occupy a fraction of the space and are produced at a fraction of the cost compared to their early counterparts, making them an essential part of power conversion systems.

The behavior of a semiconductor diode is characterized by several key parameters, the most important being the forward voltage, also known as the turn-on voltage (Kulkarni and Khaparde, 2004). This voltage is the minimum required to make the diode conduct in the forward direction. The actual turn-on voltage depends on both the material properties of the diode and the type of rectifier being used. For example, in a typical silicon diode rectifier, the turn-on voltage is approximately 0.6 volts. In contrast, germanium diodes exhibit a lower turn-on voltage of approximately 0.2 to 0.3 volts, making them more suitable for applications where low voltage drops are critical. Furthermore, silicon Schottky diodes, which are often used in high-frequency and high-efficiency applications, also exhibit a turn-on voltage in the same range of 0.2 to 0.3 volts, but they offer faster switching characteristics and lower forward losses.

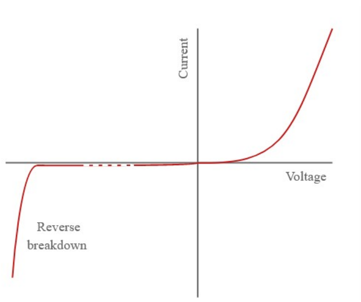


Figure 2. Diode character

In addition to its forward bias operation, the diode in a rectifier circuit must be able to handle reverse voltage conditions. When the diode is reverse biased, it ideally should not conduct any current. However, if the reverse voltage exceeds the diode's reverse breakdown voltage, the diode may enter into breakdown mode, which results in failure and potential damage to the rectifier circuit. The reverse breakdown voltage of a diode is significantly higher than the forward turn-on voltage, providing a safe margin in typical operating conditions. In the reverse direction, the diode essentially acts as an insulator, blocking current flow, but if the reverse voltage becomes too high, the diode's insulating properties can fail, leading to reverse breakdown. This phenomenon is often depicted in voltage vs. current characteristics, where the reverse breakdown region occurs well beyond the typical operating conditions of the diode.

DOI xxxxxx

In the context of the single-phase full-wave rectifier circuit used in R-L load systems, understanding the characteristics of diodes is critical for achieving efficient voltage conversion and maintaining voltage stability (Fauzi et al., 2024). The diodes must be chosen not only for their ability to handle the expected forward current but also for their ability to withstand the reverse voltage conditions encountered during the alternating current (AC) cycle. The rectifier circuit design must account for these factors to minimize power losses, ensure efficient operation, and prevent damage from excessive reverse voltage.

Moreover, the voltage stabilization in full-wave rectifiers requires careful selection of diodes to ensure that the output DC voltage remains as smooth as possible, even under varying load conditions. The diode's turn-on voltage and reverse breakdown characteristics directly influence the output waveform and efficiency of the rectification process. In particular, diodes with lower turn-on voltages and higher reverse breakdown voltages provide greater efficiency and reliability in rectifiers, especially when connected to complex loads such as resistive-inductive (R-L) circuits.

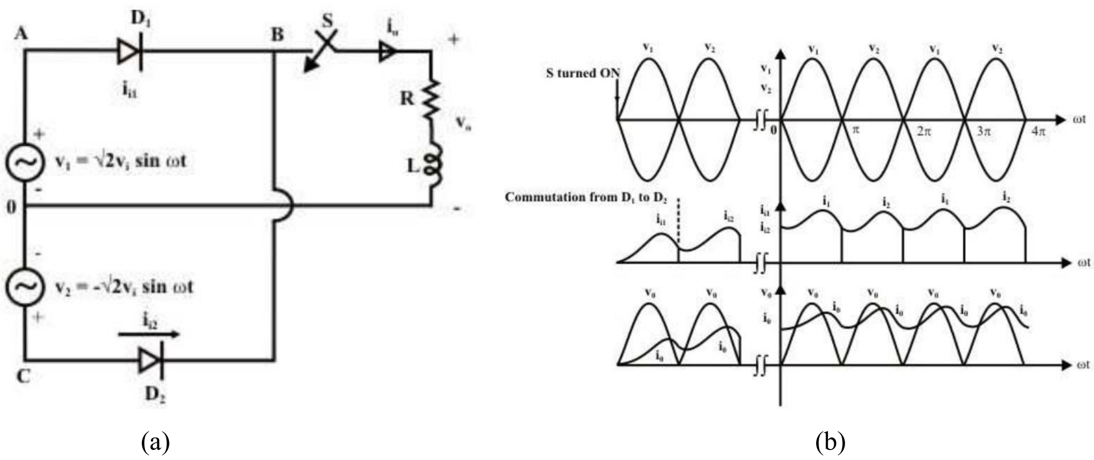
In the context of engineering research focused on power electronics, understanding the operational parameters and behavior of diodes in a rectifier circuit is critical (Nugraha et al., 2023). These insights are essential for the design optimization of power conversion systems, where achieving high efficiency, stability, and reliability is of paramount importance. As such, this understanding contributes significantly to the broader goals of improving voltage regulation, maximizing system efficiency, and enhancing the durability of power electronics systems used in various industrial and consumer applications.

3. Results and discussion

In the context of power electronics and rectifier circuits, diodes are fundamental components that enable efficient conversion of alternating current (AC) into direct current (DC). This section will delve deeper into the use of diodes within single-phase uncontrolled full-wave rectifiers, specifically when connected to a single-phase AC generator source.

As previously discussed, diodes exhibit the unidirectional current conduction property, which makes them ideal for rectification purposes. A significant issue in uncontrolled single-phase half-wave rectifiers is the poor output voltage quality and high input current ripple. These deficiencies are primarily due to the single diode conducting during only half of the AC cycle, leading to voltage fluctuations and a substantial ripple in the DC output. Furthermore, the presence of DC components in the input current can induce transformer saturation and other operational inefficiencies, causing distortion in the power supply system. Additionally, the DC output voltage of a half-wave rectifier is relatively low compared to other rectifier configurations.

To address these challenges, full-wave rectifiers offer a more reliable solution by utilizing multiple diodes, effectively doubling the frequency of the output voltage and significantly reducing the ripple factor. This results in a higher average and RMS output voltage, improving the overall quality of the DC power supplied to the load. Consequently, full-wave rectifiers are commonly preferred over half-wave rectifiers in applications requiring more stable and efficient DC conversion.



(a) (b)

Figure 3. Split Supply Single Phase Rectifier Uncontrolled Load Supply RL

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Figure 3 illustrates the **circuit diagram** and **waveform** of a **single-phase split supply, uncontrolled full-wave rectifier** connected to an **R-L load**. In this configuration, the split power supply is assumed to be derived from the secondary winding of an **ideal middle-tapped transformer**, which is modeled without any internal impedance. This idealized assumption simplifies the analysis and allows for a clearer understanding of the rectifier's performance under optimal conditions.

When the switch is closed at the positive zero junction of voltage v_1, diode D1 becomes forward-biased, initiating current flow through the load. At this stage, currents i_0 and i_i1 begin to rise through diode D1. As the voltage v_1 transitions from a positive to negative phase, it crosses zero, causing i_0 and i_i1 to continue to flow, keeping diode D1 conducting. This continuous conduction leads to a scenario where the voltage across diode D2 is given by $V_{CB}=V_2-V_1$. When the voltage at the negative zero junction of vi is reached, diode D2 becomes forward-biased. This allows the current i_0 to shift from D1 to D2, thereby causing the load voltage v0 to become equal to v_2, and diode D1 starts to block the voltage $V_{AB}=V_1-V_2$

As the circuit progresses, current i_0 continues to increase through diode D2, eventually reaching a steady-state level after a few cycles. The steady-state waveform, depicted in Figure 3(b), begins from t=0 and continues in a consistent manner thereafter. This steady-state operation, where the current remains positive, is characteristic of the continuous conduction mode (CCM) of the rectifier.

In continuous conduction mode, the rectifier operates without any interruption in current flow, ensuring smooth DC output and low ripple in the load current. This mode is particularly crucial for applications requiring stable power delivery, such as in linear DC voltage regulators and industrial power supplies. The R-L load serves as a typical example of a real-world load that demands consistent and reliable DC current, making this rectifier configuration highly applicable in both academic research and practical engineering applications.

The analysis presented here aligns with the requirements for a technical journal, conference proceedings, or research papers in the field of power electronics and electrical engineering. It also provides a deeper understanding of the operational characteristics of single-phase full-wave rectifiers under a split supply system, with a focus on efficiency evaluation and voltage stabilization. These aspects are key considerations for engineers working on the design and optimization of rectifier circuits in modern power conversion systems. From the discussion above, it is obtained

For $0 \le wt < \pi$

$v_0=v_1$

$i_0=i_{i1}$

For $\pi \le wt < 2\pi$

$v_0=v_2$

$i_0=i_{i2}$

Since v_0 is periodic on the interval π

$$V_{0AV}=\frac{1}{\pi}\int_0^{\pi} V_0\,dwt=\frac{\sqrt{2V_i}}{\pi}\int_0^{\pi} sinwtdwt=\frac{2\sqrt{2V_i}}{\pi}$$

$$Vorms=\sqrt{\frac{1}{\pi}\int_0^{\pi} 2V_I^2\sin^2 wt\,dwt}=V_i$$

$$Voff=\frac{V0rms}{VoAV}=\frac{\pi}{2\sqrt{2}}$$

$$VoRF=\sqrt{V_{off}^2-1}=\frac{\sqrt{\pi^2-8}}{2\sqrt{2}}$$

Both the form factor and the ripple factor show appreciable improvements in the half-wave counter section.

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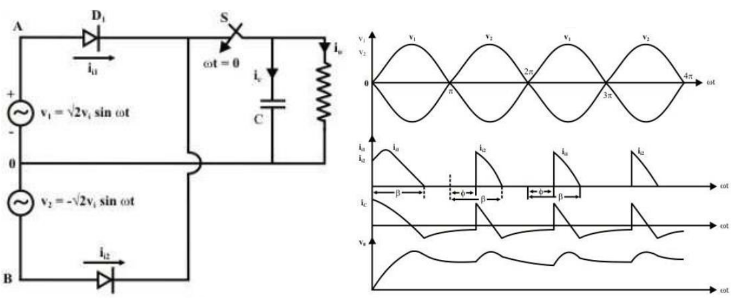

a) b)

Figure 4. Split Supply Single Phase Rectifier Uncontrolled Capacitive Load Supply

A single-phase full-wave rectifier does not inherently provide a perfectly smooth DC voltage due to the presence of ripple currents. When connected to a resistive load, the rectifier generates a ripple current that can significantly affect the performance of the system, leading to fluctuations in the output voltage. These fluctuations can be undesirable in most power supply systems, where a stable and steady DC output is required for sensitive loads. To mitigate this issue, a filtering capacitor is often added across the load resistance. This approach, commonly used in both half-wave rectifiers and full-wave rectifiers, helps in reducing the ripple and smoothing the output.

When the capacitor is initially in a discharged state, diode D1 becomes forward biased as soon as the switch S is closed at t=0, and the circuit begins to conduct. During this phase, diode D2 remains reverse biased, effectively preventing current flow through it. The output voltage follows the input AC voltage as the capacitor begins charging. Diode D1 carries both the capacitor charging current and the load current. As the circuit progresses to a specific time t, the sum of these two currents reaches zero, and the current tends to reverse, pushing the system into a negative direction.

At this critical point, diode D1 becomes reverse biased, effectively disconnecting both the load and the capacitor from the power supply. As a result, the capacitor discharges through the load until time t=+, at which point the voltage across the capacitor v2 becomes greater than the output voltage v0, and diode D2 is forward biased. Diode D1 remains reverse biased throughout this phase, and diode D2 now conducts, allowing the capacitor to continue discharging until t=+. The cycle repeats continuously, resulting in a smoother output voltage.

This operation leads to a scenario where the ripple voltage is significantly reduced, though not completely eliminated. The capacitor charging and discharging cycles are designed to reduce the ripple frequency and smooth the DC output. The effectiveness of this smoothing mechanism largely depends on the capacitance of the capacitor and the load characteristics. For applications requiring low ripple and high-quality DC voltage, the capacitance value must be chosen carefully based on the load demand and the ripple reduction desired.

In engineering practice, the implementation of a capacitor filter is a fundamental technique for improving the performance of rectifier circuits, particularly in power supplies used in industrial applications, communication systems, and electronic devices. Understanding and optimizing these systems are essential for ensuring that rectifiers deliver a reliable and stable DC voltage with minimal ripple, meeting the requirements for efficiency and voltage stabilization in modern electrical engineering designs.

From the discussion above, we get

$$For\ \pi+\varphi \le wt \le \pi+\beta$$

$$V0 = V2 = -\sqrt{2Vi}\,SINwt$$

$$i_{i2} = i_c + i_i = C\frac{dv0}{dt} + \frac{V0}{R}$$

$$¿\,I_{I2} = \frac{-\sqrt{2Vi}}{R}\left(wRCcoswt + sinwt\right)$$

$$I_{I2} = \frac{-\sqrt{2Vi}}{R}\left(1+w^2R^2C^2\right)^2\cos\left(\pi+\theta-wt\right);$$

$$Where\,\theta = \tan^{-1}\frac{1}{wRC};\ at\ wt = \pi+\beta,\ ii1 = 0\ so\ \beta-\theta = \frac{\pi}{2}$$

DOI xxxxxx

$$Again\,for\beta \le wt \le \pi+\varphi$$

$$iil=0\,;C\frac{dv\,0}{dt}+\frac{V\,0}{R}=0\,;V\,0\left(wt=\beta\right)=\sqrt{2Vi}\,sin\beta=\sqrt{2Vi}\,cos\theta$$

$$V_0=\sqrt{2\,Vi}\,cos\theta$$

$$at\;wt=\pi+\varphi,V\,0=\sqrt{2}\,sin\varphi$$

$$\sqrt{2}\,sin\varphi=\sqrt{2\,Vi}\,cos\theta$$

$$¿\,sin\varphi=cos\theta\,e^{-\left(\frac{x}{2}-\theta\right)tan\theta}$$

Hence, φ can be done. *Peak to peak ripple* in v0 is

$$V_{0\,PP}=\sqrt{2}Vi\left(1-sin\varphi\right)$$

It can be shown that for the same R and C, $V0$pp is smaller than the half-wave rectifier. The PIV rating of the diode remains the same as $V0$pp..

4. Conclusion

Based on the comprehensive analysis and design considerations presented in the previous sections, several key conclusions can be drawn regarding the performance and efficiency of the single-phase full-wave rectifier circuit with an R-L load in a split supply system**:**

1. It is evident that an uncontrolled full-wave single-phase rectifier can be constructed using two diodes, which significantly improves the performance compared to a half-wave rectifier. Through theoretical analysis and simulation, it has been demonstrated that for a given resistive (R) and capacitive (C) load, the peak-to-peak output voltage V0pp of the full-wave rectifier is lower than that of a half-wave rectifier. This outcome emphasizes the voltage regulation capability of the full-wave rectifier when used in applications requiring a steady DC output.
2. The uncontrolled full-wave single-phase rectifier exhibits a reduced ripple factor compared to a half-wave rectifier, primarily due to the use of two diodes in the rectifying process. This configuration results in a more stable DC output voltage, as the rectification process occurs during both halves of the input AC cycle. Consequently, the voltage ripple is minimized, enhancing the efficiency of the power conversion and making it more suitable for sensitive loads in practical applications such as power supplies and electronic devices.

Credit authorship contribution statement
Author Name: Conceptualization, Writing – review & editing. **Author Name**: Supervision, Writing – review & editing. **Author Name**: Conceptualization, Supervision, Writing – review & editing.

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