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Application and Types of Rectifier Circuits

This paper will be an exploration of the application and types of rectifier circuits, and will include some of their history and the significant people that contributed to their discovery and use. A rectifier is a circuit which is used to change an AC voltage into a DC voltage. The problem of changing an AC voltage to a DC voltage is not a recent one, and has been tackled many times by many different people as early as the early 1900's.

Having access to DC power is important because the majority of electronics operate on DC power. Despite DC power being extremely common, the transmission of electric power is more efficient when transported as AC, which is a conversation that dates back to the times of Nikola Tesla and Thomas Edison. Regardless, AC power is used for transmitting electricity, and DC power is used by many consumer electronic devices, so we need a way to change between the two. A rectifier circuit (so called because it straightens out an alternating current) is the circuit used to produce a DC voltage when provided with an AC voltage. As such, if you were to break open a device that plugs into a wall socket and inspect the circuits inside, you would very likely find a rectifier circuit.

As noted, DC voltage is used by the majority of consumer electronics, including cell phones, computers, televisions, microwaves, and modern LED lights to name a few. It is likely that in a given day you will interact with devices that collectively rely on hundreds of rectifier circuits, so efficient conversion of AC to DC is desirable and can have a profound impact on both the energy consumption, and the amount of components that are produced so that any device can operate properly.

Operation of Rectifier Circuits

Alternating current, as shown by its name, alternates between a positive current and a negative current as time progresses, and as such it pushes and pulls the current in whatever circuit is connected to it. Modern rectifier circuits are built with semiconductor diodes (usually made of silicon) and operate on the idea that a diode only conducts eletricity in one direction. So, when the AC source is pushing current through the diode, the diode allows the current to flow through, but when the AC source attempts to pull the current back, the diode stops the flow of current, preventing a negative voltage from appearing across the diode.

This phenomenon makes it so that the negative component of the AC input is completely removed, and naturally, the positive component is all that remains (Sinclair). The resulting average DC voltage that results is hence positive, whereas the average voltage of the AC input is always 0 V. The output of that rectifier is then put through other stages of processing to change its waveform from a half-sine shape to a steady DC voltage.

It is good to note that current flow through a diode is not ideal as it has been explained up to this point. The current through a diode does not occur when the voltage is only just above 0 V. As we learned in lecture this year, the voltage required across a diode such that it allows current to pass through can be approximated with the constant drop model at 0.7 V. The current-voltage characteristic of a diode is not simple, but that rough approximation is enough in most situations. This can have an affect on the operation of a rectifier circuit. When the AC input to a rectifier circuit is relatively small, say around 5 V_{pk}, that 0.7 V drop can make a significant difference in the DC output of the circuit. On the other hand, if the required voltage output of a rectifier is an order of magnitude or more higher, then the 0.7 V drop won't have as much of an effect and can be considered negligible.

As consumer electronics are being pushed towards lower operating voltages, the 0.7 V drop is playing a bigger role in the design of rectifier circuits. Other circuits, such as precision rectifier circuits as will be covered later in this paper, make use of op-amps or other components to emulate an ideal diode and solve this problem.

When designing a rectifier circuit, there are some key parameters of the output to keep in mind that can have an effect on the performance of the device. Because the translation of an AC source to a DC source is not perfect, the output waveform will likely result in some ripple. As such, the ripple factor is an important element of consideration. If the device that requires a DC output is sensitive to small changes in that DC power source, a poorly designed rectifier circuit can cause it to malfunction. As a reservoir capacitor is commonly used to keep the voltage on the output from dipping with the input, a heavy load on the circuit can cause a larger ripple. "When the current taken by the load is negligibly small, the output voltage is almost perfectly smooth DC. When an appreciable amount of current is being drawn, however, the output contains fluctuations of lower amplitude. This is because the reservoir capacitor is supplying current during the time that the diodes are not conducting" (Sinclair).

Another important consideration when designing a rectifier circuit is the peak inverse voltage (PIV). The PIV is the voltage that the diode experiences when it is reverse biased and not conducting electricity. If the PIV exceeds the breakdown voltage of the diode in use, it can lead to catastrophic effects as the voltage across the diode will suddenly appear negative. A suggestion is made to be conscious of the breakdown voltage of a specific diode when building a circuit, "It is usually prudent ... to select a diode that has a reverse breakdown voltage at least 50% greater than the expected PIV" (Sedra and Smith).

Common Types of Rectifier Circuits

The rectifier circuit roughly explained earlier includes only a diode and a capacitor (acting as a reservoir capacitor) to transfer an AC source into a DC output. This rectifier circuit is commonly referred to as a half-wave rectifier because it only allows half of the input wave to come through. The benefits of a half-wave rectifier are few, though there are certainly use cases for it. The largest benefit of a half-wave rectifier is the low cost. Because it uses only a single diode and capacitor, the circuit is extremely cheap to manufacture. On the other hand, the ripple factor of the rectifier circuit is significantly higher when using a half-wave rectifier circuit.

An alternative to the half-wave rectifier is the full-wave rectifier. The full-wave rectifier behaves mathematically as the absolute value of the input source. When the AC input shows a negative voltage, it is effectively inverted and becomes a equivalent positive voltage on the output. These can be realized in several different combinations, but the most common are the center-tap and bridge rectifiers. A full bridge rectifier uses a net of 4 diodes that are configured in such a way that when the voltage from the AC source is positive the current flows through half of the circuit, and when the AC source is providing negative voltage the circuit flows through the other half. The voltage flowing through the negative half of the circuit is coming from the negative terminal of the AC source, and because it is in its negative cycle the voltage appears positive to the relative ground, and the voltage on the output is positive as well. This configuration allows the input waveform to pass through when it is positive, and when it is negative it is effectively inverted and allowed to pass through once again. The downside of the full-bridge rectifier circuit is that it takes four diodes to accomplish this task. This makes it significantly more expensive when compared with the half-wave rectifier from earlier, but it is much easier to remove ripple because the output waveform reaches the maximum twice as often.

An alternative to the bridge rectifier circuit is the center-tap rectifier. A downside of this circuit is that it can only be used in conjunction with a transformer on the input. This is because the theory of a center-tap rectifier relies on attaching the very center of the transformer to the ground reference, so that when the AC input switches from positive to negative, the negative terminal of the center-tapped transformer appears positive to that side of the circuit. Then, by placing a diode on each end of the transformer and pointing towards the load, you receive a full-wave rectified output. While it requires the use of a transformer on the input, this usually isn't an issue because a transformer is likely already in place, especially if the circuit is being built to use the input from something like the wall power in your home which is fit for general use. This rectifier provides a benefit over the full-bridge rectifier circuit because it uses only two diodes instead of four, which makes it more cost effective.

Other Types of Rectifier Circuits

There are also other forms of rectifiers which are not discussed in the textbook. Such rectifiers rely on other types of components, such as the thyristor. The thyristor can be thought of as a two BJT transistors overlaid such that they share a PN junction. The thyristor is similar in theory to a voltage controlled diode, but when the thyristor's gate is supplied with current the thyristor doesn't turn off until the forward current is removed. Similar to diodes, the thyristor does not allow reversed current. The thyristor is also known by the name *silicon-controlled rectifier* (SCR). It differs from a typical diode because it blocks forward current if there isn't a gate pulse provided.

Because a gate pulse can be used to select the exact time that the SCR starts conducting, using a SCR in a rectifier circuit can allow for more control in the output of the rectifier circuit that it is being used in. Changing the time when the SCR starts conducting relative to the period of the AC waveform allows for control over the resulting DC voltage that the output of the circuit sees. Despite being called a rectifier, the SCR can be applied in the design of an inverter, which converts a DC source into an AC output, essentially the opposite of a rectifier.

Another benefit of the thyristor is the large amount of forward current that it is able to deliver. In high-power applications, the thyristor is an effective tool for accurate rectification. Such devices that might rely on high-power rectification are items such as "dimmable lamps, power regulators, and motors" (Markad).

Rectifier circuits make an appearance in the design of switched-mode power supplies (SMPS). Because an SMPS switches the internal components on and off rapidly to preserve power and improve efficiency, the device will require either at least one rectifier on the output. An SMPS will also usually be powered by some form of AC source, so the input will need to be rectified as well before being put through the pipeline of the power supply. The rectifier on the output of the SMPS can often be improved by the use of a Schottky diode. A Schottky diode differs from a normal diode because it is a semiconductor material placed next to a metal instead of another semiconductor material. Schottky diodes possess a number of advantages over their standard PN-junction counterparts. They possess a lower forward voltage drop — usually around 0.2 V to 0.4 V — than a standard 0.7 V diode, which allows them to be more efficient on the output rectification step of the SMPS. This is even more crucial for low-voltage SMPS designs, such as those used in 3.3 V or 5 V devices.

Another advantage of the Schottky diodes in an SMPS is the high switching speed that they possess. This is because they lack the charge storage associated with the P-N junction, and as such don't feel the same diffusion capacitance effect that the standard diodes feel. Despite these advantages, Schottky diodes aren't always used in place of normal diodes for a few reasons. Primarily, the reverse breakdown voltage is lower than in a normal diode, and the cost of Schottky diodes is higher on average than a standard P-N junction diode.

The First Rectifier Circuits and Devices

The first rectifier circuits that were invented relied on devices that are no longer in use because of their lack of reliability and relative safety concerns. An example of such a device is the electrolytic rectifier, which was made by placing two different metals in an electrolytic solution such that direct current flowing one way sees less resistance than in the other direction. Such a rectifier was unsafe and unreliable because it was temperature sensitive and some models would not be able to operate in temperatures as low as 86 degrees Fahrenheit. An electrolytic rectifier also suffered from a breakdown voltage when reverse biased which limited the number of useful applications for the device.

Other early rectifiers/diodes included plasma type rectifiers that took several different forms. A common rectifier in use in the early 1900's was the mercury-arc rectifier. Such a rectifier used a cathode submerged in liquid mercury with an anode suspended above the pool. The rectifer relied on an arc to form between the cathode pool and the suspended anode, and could sustain high power levels and up to six phases of AC current.

In the early development of radio technology, the need for rectifying an AC radio signal gave birth to the crystal detector. While these are no longer in use, they served as some of the first semiconductor devices and can date back to as early as the 1870's.

Other Applications of Rectifiers

Rectifiers convert AC sources into a DC output, but they aren't only used for the sake of power delivery. As I learned in my study of the crystal detector, rectifier circuits are also used to demodulate an AM radio signal. Because the signals are transmitted as AC signals with the varying amplitude of the signal encoding the "message", the AC signal needs to be demodulated in order to receive the original waveform being transmitted.

A rather novel area of study is the concept of wireless power transfer (WPT). Wireless power transfer relies on the concept of radio-frequency (RF) to direct current conversion, which is another way to think of rectification. With WPT, it is essential to make sure that each part of the pipeline is as efficient as possible, especially when it is being employed to transfer a lot of power quickly such as in the case of electrical vehicles. The benefits of being able to use WPT for EV's are apparent, but WPT can be required in some use cases, such as in implantable devices where physical contact may not be an option. When an RF signal is conducted wirelessly, it is conducted as an alternating signal, and rectification is needed to transform the output to a DC source suitable for power delivery. There is a lot of research currently being put toward maximizing the efficiency of rectifiers because any loss in efficiency can have a large impact in the performance of a system.

I found it interesting when an engineer needed to increase the DC voltage in a system and decided the best way to do that was by inverting the DC voltage to an AC signal, then using a transformer to step up the voltage, and finally rectifying the resulting AC waveform. It didn't occur to me that this can be the best way to step up a DC voltage, but that makes it even more important to make sure that the rectification (and inversion) processes are as efficient as possible.

Conclusion

There is no doubt that rectifier research will persist as time goes on. Historically, numerous different approaches have been taken in order to solve the problem of converting an AC source into a DC output. While the attempts to rectify an AC source looked wildly different in the early history of electrical discovery, the modern day solutions seem to have been optimized. The vast majority of rectifier circuits and devices in the modern day are constructed with silicon or germanium based diodes, and that doesn't seem like it will change any time soon.

Using those diodes in the purpose of rectifying small power systems (those around 3-20 V such as consumer electronics), is extremely common because they fit the purpose so well. But, as the solutions have become more and more similar, so have the problems. As consumer electronics bend toward more consistent practices, the designers choose to rely on existing technologies and solutions to the problems that they face. Additionally, the standardization of circuit design practices leads to the increased consumption of similar componens. As supply follows the demand, the cost of those components will decrease and the designers of more consumer electronics will choose to utilize those circuits and designs in further products.

A wide range of rectifier circuits are used for a wide range of purposes. I think that the developments in high power WPT systems are interesting and could revolutionize several different markets, including the electrical vehicle market. Of course, rectifying an input is usually only one component in a larger system, and there might be other areas where optimization plays a larger role than in the well-defined rectifier space. That being said, advances in the field of electrical engineering merit the expertise and perfection of every part of a given electrical system.

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