Using Rectifiers in Voltage Multiplier Circuits

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Systems designs frequently call for a high voltage, low current power source that needs only minimal regulation. A few familiar examples are CRT circuits, electrostatic copiers, and photoflash applications. Required voltages typically range from 10 to 30 kV and the current demand rarely exceeds 5 milliamperes.

When your design requires this type of power source, you may want to consider a voltage multiplier circuit. They are inexpensive, easy to design, versatile, and can provide virtually any output voltage that is an odd or even multiple of the input voltage.

This article explores the basic operation of multiplier circuits and discusses guidelines for electronic component selection. Since General Semiconductor is the industry’s leading manufacturer of rectifier products, we will place special emphasis on selecting rectifier diodes for multiplier circuits.

BASIC OPERATING PRINCIPLES

Most voltage multiplier circuits, regardless of their topology, consist chiefly of rectifiers and capacitors. Figure 1. shows three basic multiplier circuits.

The operating principle of all three circuits is essentially the same. Capacitors connected in series are charged and discharged on alternate half-cycles of the supply voltage. Rectifiers and additional capacitors are used to force equal voltage increments across each of these series capacitors. The multiplier circuit’s output voltage is simply the sum of these series capacitor voltages.

A wide variety of alternating signal inputs are used with multiplier circuits. The most popular are sine and square wave inputs. For simplicity, this discussion will be limited to sine wave inputs; the calculations become somewhat more involved with asymmetrical signals.

Voltage Doublers - Figure 1A. shows a half-wave voltage doubler circuit. It functions as follows. On the negative half-cycle of the input voltage, capacitor \( C_1 \) charges, through rectifier \( CR_1 \), to a voltage of \( V_m \). On the positive half-cycle, the input voltage, in series with the voltage of \( C_1 (V_{C1} = V_m) \), charges capacitor \( C_2 \) through rectifier \( CR_2 \) to the desired output voltage of \( 2 V_m \). Capacitor \( C_1 \), which aides in the charging of a capacitor \( C_2 \), sees alternating current (“AC Cap”) while \( C_2 \) sees only direct current (“DC Cap”). In this circuit, the output voltage and the input signal have the same ripple frequency.

The same operating principle extends to the full-wave voltage doubler circuit of figure 1B. On the negative half-cycle of the input voltage, capacitor \( C_2 \) is charged through rectifier \( CR_2 \) to a voltage of \( V_m \). On the positive half-cycle, capacitor \( C_1 \) is also charged to a voltage of \( V_m \), through rectifier \( CR_1 \). The series voltages of capacitors \( C_1 \) and \( C_2 \) (\( V_{C1} = V_{C2} = V_m \)) yield the desired output voltage: \( 2 V_m \). In this case, capacitors \( C_1 \) and \( C_2 \) are “DC capacitors”; they see no alternating current. The output ripple frequency of the full-wave doubler is twice that of the input signal.
Capacitor selection - The size of capacitors used in multiplier circuits is directly proportional to the frequency of the input signal. Capacitors used in off-line, 60 Hz applications are usually in the range of 1.0 to 200 µF while those used in higher frequency applications, say 10 kHz, are typically in the range of 0.02 to 0.06 µF. In practice, it is usually easier, and less costly, to use the same large capacitance value for all capacitors, both "AC" and "DC" type. The overall capacitive reactance of the circuit must be considered, however, to determine the largest permissible value.

The voltage rating of capacitors is determined solely by the type of multiplier circuit. In the half-wave doubler circuit of figure 1A., C4 must be capable of withstanding a maximum voltage of Vm, while C2 must withstand a voltage of 2 Vm. In the full-wave doubler circuit of figure 1B., both C1 and C2 must withstand voltages of Vm. The half-wave voltage tripler of figure 1C. requires C1 to withstand a voltage of Vm, and both C2 and C3 to withstand voltages of 2 Vm. A good rule of thumb is to select capacitors whose voltage rating is approximately twice that of the actual peak applied voltage. For example, a capacitor which will see a peak voltage of 2 Vm should have a voltage rating of approximately 4 Vm.

RECTIFIER DIODE SELECTION

Several basic device parameters should be considered:

Repetitive Peak Reverse Voltage (V_{RPM}) - Repetitive peak reverse voltage is the maximum allowable instantaneous value of reverse voltage across the rectifier diode. Applied reverse voltages below this maximum value will produce only negligible leakage currents through the device. Voltages in excess of this maximum value, however, can cause circuit malfunction - and even permanent component damage - because significant reverse currents will flow through the device. For example, Vishay General Semiconductor’s GP02-40 rectifier diode has a peak reverse voltage rating (V_{RPM}) of 4000 V, maximum. Applied reverse voltages of 4 kV or less will produce a maximum reverse leakage current, I_{L}, of 5 µA through the device when operated at room temperature (25 °C). In most cases, this leakage current is considered negligible, and the device is said to be completely blocking (I_{L} = 0).

In the case of the three circuits of figure 1., the maximum reverse voltage seen by each rectifier diode is 2 Vm. So devices must be selected with reverse voltage (V_{RPM}) ratings of at least 2 Vm.

Reverse Recovery Time (t_{rr}) - In general terms, reverse recovery time is a measure of the time needed for a rectifier diode to reach a state of complete blocking (I_{L} = 0) upon the application of a reverse bias. Ideally, this time should be zero. In reality, however, there’s a finite period of time in which a stored charge at the diode junction must be “swept away” before the device can enter its blocking mode. This stored charge is directly related to the amount of forward current flowing through the device just prior to the application
of the reverse bias. Fortunately, since operating currents are very low in multiplier circuits, reverse recovery times are kept to a minimum. Nevertheless, \( t_{rr} \) plays an important role in multiplier design.

When selecting rectifier diodes, the frequency of the input signal to the multiplier network must be considered. For symmetrical signal inputs, the device chosen must be capable of switching at speeds faster than the rise and fall times of the input. If the reverse recovery time of the rectifier is too long, the efficiency and regulation of the circuit will suffer. In the worst case, insufficient recovery speeds will result in excessive device heating, as reverse power losses in the rectifier become significant. Continued operation in this mode usually results in permanent damage to the device.

The reverse recover time \( (t_{rr}) \) specification is very dependent upon the circuit and the conditions being used to make the measurement. Several industry standard \( t_{rr} \) test circuits exist (Figure 2. is the test circuit used for the GP02-40). Therefore, it’s very important to note which test circuit is being referenced, as the same device may measure differently on different test circuits. Furthermore, the \( t_{rr} \) specification should be used for qualitative, not quantitative purposes, since conditions specified for \( t_{rr} \) measurement rarely reflect those found in actual real life circuit operation. The \( t_{rr} \) specification is most valuable when comparing two or more devices that are measured on the same circuit, under the same conditions.

Figure 3. shows the relationship between forward current and \( t_{rr} \) in the GP02-40. As you can see, decreasing current flow in the multiplier circuit makes it possible to use higher input frequencies. An increase in current flow has the opposite effect. Ideally, the multiplier network load should draw no current.

Peak forward Surge Current (\( I_{FSM} \)) - A peak forward surge current rating is given for most rectifier diodes. Most often, this rating corresponds to the maximum peak value of a single half-sine wave (50 or 60 Hz) which, when superimposed upon the device’s rated load current (JEDEC method), can be conducted, without damage by the rectifier. This rating becomes important when considering the large capacitance associated with multiplier circuitry.

Surge currents can develop in multiplier circuits, due to capacitive loading effects. The large step-up turns ratio between primary and secondary of most high voltage transformers causes the first multiplier capacitor \( C_1 \), secondary side) to be reflected as a much larger capacitance into the primary. For example, a transformer with a turns ratio of 25 will cause a 1.0 \( \mu \)F capacitance to be reflected into the primary circuitry as a capacitance of \((1.0)(25) \mu \text{F}, or 625 \mu \text{F.} \) At circuit turn-on, large currents will be developed in the primary side as this effective capacitance begins charging.

Figure 3. \( t_{rr} \) as a Function of Forward Current

On the secondary side, significant surge currents can flow through the rectifiers during initial capacitor charging at turn-on. The addition of a series resistance \( (R_S) \) can greatly reduce these current surges, as well as those in the primary circuitry. For example, the GP02-40 has a forward surge rating, \( I_{FSM} \), of 15 A. Considering a maximum secondary voltage of 260 V\(_{\text{RMS}}\), 60 Hz, the calculation of \( R_S \) is as follows:

\[
R_S \geq \frac{V_{\text{peak}}}{I_{\text{FSM}}} \quad \text{eq. 1}
\]

\[
R_S \geq \frac{(1.41)(260)}{15} \geq 24.4 \Omega
\]

**Other Parameters** - Of lesser significance are the forward current rating, \( I_0 \), and maximum forward voltage, \( V_F \).

**Forward current, \( I_0 \)** - As stated earlier, in the ideal multiplier configuration the load will draw no current. Ideally, the only significant current flow through the rectifiers occurs during capacitor charging. Therefore, devices with very low current ratings (hundreds of milliamperes) can be used. It must be noted, however, that the forward current and forward surge current ratings are related, since both are a function of silicon die area. Generally speaking, devices with a high surge current rating, \( I_{FSM} \), will also have a high forward current, \( I_0 \), rating, and vice versa.

**Forward Voltage, \( V_F \)** - In practice, the forward voltage drop, \( V_F \), of the rectifiers does not have a significant effect on the multiplier network’s overall efficiency. For instance, the GP02-40 has a typical forward drop of 2.0 V when measured at a current of 100 mA. A half-wave doubler with an 8 kV output will have less than 0.05% (2 x 2 V/8 kV) loss in efficiency due to the forward voltage drops.
HIGHER ORDER CASCADE MULTIPLIER

Still higher voltages are possible by using the cascade multiplier circuit shown in figure 4. The output voltage is calculated as:

\[ V_0 = (n)(V_m), \text{ as } I_L \rightarrow 0 \quad \text{eq.2} \]

where \( n \) = number of capacitors, or diodes, assuming equal value capacitors, ideal diodes and symmetrical signal input.

In theory, one can obtain any incremental output voltage increasing the value of \( n \). In practice, however, voltage regulation and efficiency become increasingly poor as \( n \) increases. The potential for voltage arcing must also be considered as the value of \( n \) increases, and when higher output voltages are required. Careful mechanical design can minimize arcing, to a large extent.

From a pure circuits standpoint, voltage multipliers are relatively easy to design. The selection of circuit components, however, is one facet of the “overall design” that should not be taken for granted or trivialized. Careful consideration of all component parameters is the only way to ensure both reliable and predictable circuit performance. Put another way, ideal circuits require ideal circuit components.

Figure 4. Cascade Multiplier