Silicon Zener Diodes, Bidirectional Zener Diodes

Zener diodes are special silicon diodes which have a relatively low, defined breakdown voltage, called the Zener voltage.

At low reverse voltages a Zener diode behaves in a similar manner to an ordinary silicon diode, that is , it passes only a very small leakage current. If, however, the reverse bias is increased until it reaches the breakdown region, then a small reverse voltage increase causes a considerable increase in leakage current; the reverse current is then called the Zener current. The characteristics of a Zener diode operating under reverse breakdown conditions are similar to those of a struck glow discharge tube. Because of this, Zener diodes can be used in a similar way, i.e. as stabilizers, limiters, ripple reduction elements, reference voltage sources, and also as DC coupling elements with a constant voltage drop.

Characteristics

The slope of the reverse breakdown characteristic defines the static differential resistance $r_{zu} = dV_Z/dI_Z$, which, in turn, comprises a dynamic (or inherent differential) resistance r_{zj} and a thermal differential resistance r_{zth}.

Use of the dynamic resistance alone for characterizing the performance of a Zener diode is only satisfactory if the ambient temperature can be assumed to be constant, and the Zener current variations are so rapid that the junction temperature is unable to follow them. A generalized design approach requires that the effect of slow Zener current variations is also taken into consideration, in which case the design must be based on the static differential resistance value r_{zu}, which is the sum of the dynamic and the thermal differential resistance:

$$r_{zu} = r_{zj} + r_{zth}$$

At T_{amb} = const.,

$$V_Z = f(I_Z, T)$$

so that

$$\frac{dV_Z}{dI_Z} = \left(\frac{\delta V_Z}{\delta I_Z}\right)_T + \left(\frac{\delta V_Z}{\delta T}\right)_{I_Z} \frac{dT}{dI_Z} \qquad (1)$$

Setting

$$\frac{dV_Z}{V_Z \cdot dT} = \alpha_{VZ} \quad (2) \qquad \text{and} \qquad \frac{dT}{V_Z \cdot dI_Z} = R_{thA} \quad (3)$$

yields

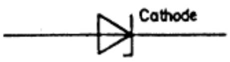
$$r_{zu} = r_{zj} + V_Z^2 \cdot \alpha_{VZ} \cdot R_{thA} = r_{zj} + r_{zth} \qquad (4)$$

where α_{VZ} is the Zener voltage temperature coefficient, T the junction temperature, and R_{thA} the thermal resistance between the junction and the ambient air.

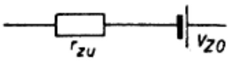
The dynamic resistance is largely dependent on current, and decreases as the Zener current increases. The temperature coefficient α_{VZ} is dependent on temperature, but only at Zener voltages below 7 V.

Circuit symbol for a Zener diode

or



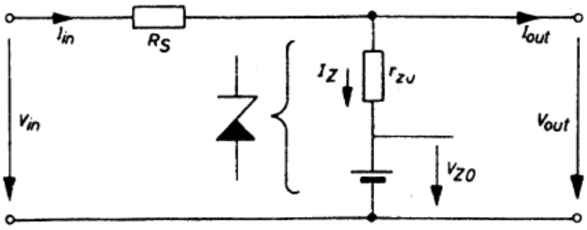
Simplified equivalent circuit diagram



V_{Z0} is the breakdown voltage, extrapolated for $I_Z = 0$.

Design of Stabilizer Circuits

To simplify the design procedure, a constant differential resistance r_z is assumed in the following expressions. Since this does not strictly apply (as has been pointed out previously), an r_z value which lies in the middle of the stabilization range should be used. It is also assumed that T_{amb} is constant.



In the above circuit, the Zener diode is replaced by an equivalent circuit comprising a constant voltage generator giving a DC voltage of V_{Z0} in series with a differential resistance r_{zu}. Other parameters in this circuit diagram are: V_{out} = output voltage, I_{out} = output current, V_{in} = input voltage, I_{in} = input current, I_Z = Zener current, and RS = series resistance.

The following equations apply

$$V_{in} - V_{out} = (I_{out} + I_Z) \cdot R_S, \qquad (5)$$

$$V_{out} - V_{Z0} = I_Z \cdot r_{zu} \qquad (6)$$

If equation (6) is combined with equation (5) one obtains

$$V_{in} = V_{out} + I_{out} \cdot R_S + (V_{out} - V_{Z0}) \cdot \frac{R_S}{r_{zu}} \qquad (7)$$

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Differentiation yields the smoothing factor

$$G = \frac{dV_{in}}{dV_{out}} = 1 + \frac{R_S}{r_{zu}} \qquad (8)$$

where I_{out} is assumed to be constant.

Because R_S is, as a rule, very much larger than r_{zu}, the smoothing factor G can be taken as being approximately equal to the ratio R_S/r_{zu}. As can be deduced from equation (8), G increases linearly with R_S (provided that V_{in} is also increased), and, if V_{in} and R_S approach infinity, the G will also approach infinity.

More important than the smoothing factor is the stabilization factor S, i.e. the ratio of a relative input voltage change to a relative output voltage change:

$$S = \frac{\dfrac{dV_{in}}{V_{in}}}{\dfrac{dV_{out}}{V_{out}}} = \left(1 + \frac{R_S}{r_{zu}}\right) \cdot \frac{V_{out}}{V_{in}} \qquad (9)$$

The stabilization factor, unlike the smoothing factor, does not increase linearly with V_{in} and R_S, but approaches a finite limit value when V_{in} and $R_S \rightarrow \infty$. In order to determine this limit value, R_S is eliminated from equation (9) by the use of equation (5):

$$R_S = \frac{V_{in} - V_{out}}{I_{out} + I_Z} = \frac{V_{in} - V_{out}}{I_{in}}$$

with the result that

$$S = \frac{V_{out}}{V_{in}} + \frac{V_{out}}{I_{in} \cdot r_{zu}} \cdot \left(1 - \frac{V_{out}}{V_{in}}\right) \qquad (10)$$

If $V_{in} \rightarrow \infty$, then this reduces to

$$S_{max} = \frac{V_{out}}{I_{in} \cdot r_{zu}} \qquad (11)$$

It can be seen that for a given Zener diode and a given load, the stabilization improves as the input voltage is increased; it should be noted, however, that the power dissipated in the diode series resistor rises at a higher rate than that at which the stabilization factor is increased. As a sensible comprise between the requirements of good stabilization and acceptable power dissipation, it is suggested that the input voltage be made about 2 to 4 times the value of the output voltage.

The output resistance presented by the stabilizer is equal to the diode series resistance R_S in parallel with the differential resistance r_{zu} of the diode. Since R_S is usually very much larger than r_{zu}, the stabilizer output resistance is virtually equal to r_{zu}. It should be noted that in this calculation R_S includes the source resistance of the input supply so that V_{in} is the source EMF.

Other important factors which must be taken into consideration in the design of a shunt stabilizer are, apart from the stabilization factor and the output resistance, the maximum admissible power dissipation and the maximum admissible Zener current. These must not be exceeded under maximum input voltage and minimum load current conditions. The following conditions must be fulfilled:

$$V_{out} \cdot \left(\frac{V_{in\,max} - V_{out}}{R_X} - I_{out\,min}\right) < P_{tot,} \qquad (14)$$

$$R_s > \frac{V_{in\,max} - V_{out}}{I_{Z\,max} + I_{out\,min}} \qquad (15)$$

Finally, steps must be taken to ensure that the output current Iout does not become excessive. If the input voltage is constant, then the Zener current decreases in the same proportion as the output current increases. However, at very small Zener currents the dynamic resistance of the Zener diode rises sharply and the stabilization performance is correspondingly degraded.

Therefore, the following conditions must be fulfilled:

$$\left(\frac{V_{in\,min} - V_{out}}{R_S} - I_{out\,max}\right) > I_{Z\,min,} \qquad (16)$$

$$R_S < \frac{V_{in\,min} - V_{out}}{I_{Z\,min} + I_{out\,max}} \qquad (17)$$

$I_{Z\,min}$ should be 5 to 10% of $I_{Z\,max}$.

Breakdown voltage (Zener Voltage) Measurements on Zener Diodes

If a Zener diode is connected to a constant current source, then at constant ambient temperature, the Zener voltage changes and approaches asymptotically a final value. This voltage change is due to the power dissipated in the junction which in turn causes a rise in junction temperature. Zener diodes with a negative temperature coefficient exhibit a Zener voltage reduction, whereas those with a positive temperature coefficient show a Zener voltage increase on application of current. The magnitude of this voltage change due to intrinsic heat generation can be derived from the relevant curves.

Because it is not practical to wait during tests until each device has reached its thermal equilibrium, it is common practice to measure the breakdown voltage of Zener diodes by application of a pulsating current of less than 1 sec duration. Under these conditions the junction temperature is the same as the ambient temperature. The magnitude of the test current used varies from type to type and is quoted in the relevant data sheets.

Therefore, designers, but especially customers carrying out acceptance tests, should allow for the fact that the Zener voltage of a device which is at thermal equilibrium will differ from that quoted in the data sheet. To arrive at an estimate of the equilibrium Zener voltage, a voltage equal to the product of Zener current and thermal differential resistance should be added to the voltage associated with the chosen current as derived from the published dynamically measured breakdown curves.

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