Basic Theory of Zener Regulation

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September 27, 2022

In the figure-1 (top), schematic $I-V$ characteristic of a Zener diode is depicted. The interesting phenomena is observed in the reverse bias of Zener diode. Up to a particular reverse voltage (say V_Z), current through Zener is only the reverse saturation current I_0, which is of the order of few μA. Just beyond V_Z, reverse current increases very rapidly and voltage across Zener remain unchanged at V_Z. The phenomena of rapid rise of Zener current at fixed Zener voltage V_Z is known as *Zener Breakdown* and the voltage V_Z is called *break down voltage*.

V_Z is Zener diode dependent property, it is independent of external circuitry as well as Zener bias. The characteristic feature of Zener breakdown at fixed Zener voltage V_Z have potential application for the purpose of fixed voltage supply. Particular circuit arrangement of Zener diode in reverse bias operating at V_Z produces fixed output voltage while the input source voltage and output load resistance can vary within a specified range.

The constancy of output voltage with variation of input voltage is specified as *line regulation* and the constancy of output voltage with variation of load resistance is known as *load regulation*. The circuit for load regulation operation of Zener is depicted in figure-1(a) and the same for line regulation operation of Zener is shown in figure-1(b).

Refer to figure-1(top), Zener breakdown starts at minimum Zener current say $I_{Z,min}$ and it is allowed upto maximum Zener current $I_{Z,max}$ limited by the maximum power dissipation in Zener diode. Zener diode have a maximum power dissipation (Joule heating) rating specified by manufacturer. If $P_{Z,max}$ is the maximum power dissipation in Zener (beyond which Zener can burnt out) then $P_{Z,max} = V_Z I_{Z,max}$. That means Zener can safely be used for the purpose of fixed voltage output when Zener current is less than $I_{Z,max}$ but greater than $I_{Z,min}$.

Load Regulation :

The necessary circuit for load regulation is depicted in figure-1(a). According to the circuit diagram,

$$V_{in} = IR_S + V_L$$

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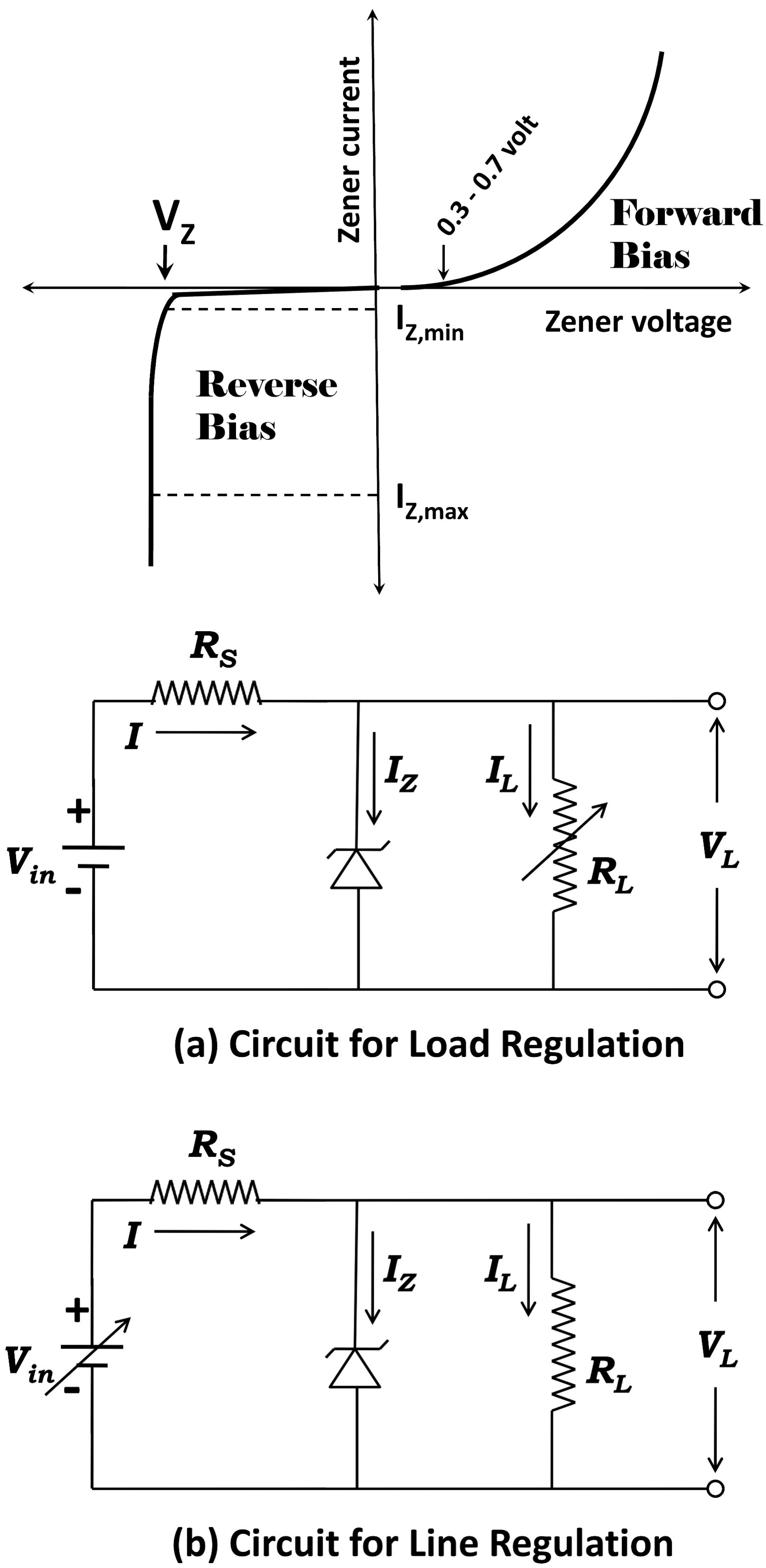

Figure 1:

In load regulation, R_L varies but $V_L = I_L R_L$ remain at fixed value of V_Z. If R_L is increased, I_L will decrease such that the product $I_L R_L$ remain at fixed value of V_Z and vise verse. Therefore,

$$\begin{aligned} V_{in} &= IR_S + V_L \\ &= (I_Z + I_L)R_S + V_L \\ &= \left(I_Z + \frac{V_L}{R_L}\right) R_S + V_L \end{aligned}$$

Now in the region of Zener regulation, $V_L = V_Z$, therefore,

$$\boxed{V_{in} = \left(I_Z + \frac{V_Z}{R_L}\right) R_S + V_Z} \tag{1}$$

For minimum value of R_L (say $R_{L,min}$), I_L becomes maximum (to keep $I_L R_L = V_L = V_Z$); but since, $I = I_L + I_Z$ so, I_Z becomes minimum at $I_{Z,min}$. On the other hand, using similar arguments, for maximum value of R_L, I_L becomes minimum which eventually gives $I_Z = I_{Z,max}$. The range of variation of R_L in load regulation is specified by the range between $I_{Z,min}$ to $I_{Z,max}$. So, from relation (1), one can obtain the range of variation of R_L for a given circuit specified by V_{in}, R_S and Zener diode information.

Line Regulation :

The required circuit is depicted in figure-1(b), in which one can tune the input source voltage and output voltage V_L across R_L remain fixed at the value of V_Z. While the V_{in} is increased, total current I will increase but I_L must remain fixed to make $I_L R_L = V_L = V_Z$. Since, $I = I_L + I_Z$, therefore, I_Z will increase to adjust the increase of I. Similarly, when V_{in} is decreased, I_Z will decrease keeping I_L fixed. So, for maximum input voltage (say $V_{in,max}$), $I_Z = I_{Z,max}$ and for $V_{in,min}$, $I_Z = I_{Z,min}$.

Numerical example - 1 : Refer to the circuit 1(a), consider 1 watt, 6 volt Zener diode (with $I_{Z,min} = 1\ mA$) is connected to $V_{in} = 12$ volt, $R_S = 100\ \Omega$. Find the range of variation of R_L such that V_L maintains a constant value.

Solution : According to above discussions, for $R_{L,min}$, $I_Z = I_{Z,min}$ and for $R_{L,max}$, $I_Z = I_{Z,max}$. Here, $P_{Z,max}$ =1 watt, V_Z =6 volt, therefore,

$$I_{Z,max} = \frac{P_{Z,max}}{V_Z} = \frac{1}{6}\ A$$

From equation (1),

$$\begin{aligned} V_{in} &= \left(I_{Z,min} + \frac{V_Z}{R_{L,min}}\right) R_S + V_Z \\ \Rightarrow\quad 12 &= \left(10^{-3} + \frac{6}{R_{L,min}}\right) \times 100 + 6 \\ \Rightarrow\quad R_{L,min} &\approx 99\ \Omega \end{aligned}$$

Suppose, $R_L = \infty$, then the Zener current becomes,

$$I_Z = \frac{12 - V_Z}{R_s} = 0.06\ A$$

which is less than the maximum Zener current $I_{Z,max}$, that means maximum value of R_L can be ∞.

Numerical example - 2 : Refer to the circuit 1(b), consider 0.5 watt, 6 volt Zener diode (with $I_{Z,min} = 2\ mA$) is connected to V_{in}, $R_S = 200\ \Omega$, $R_L = 2\ K\Omega$. Find the range of variation of V_{in} such that V_L maintains a constant value.

Solution : Given, $P_{Z,max} = 0.5\ watt$, therefore,

$$I_{Z,max} = \frac{P_{Z,max}}{V_Z} = 83.3\ mA$$

In the regulation region of the Zener diode, $V_L = V_Z = 6\ V$. When $V_{in} = V_{in,max}$ then $I_Z = I_{Z,max}$ and when $V_{in} = V_{in,min}$ then $I_Z = I_{Z,min}$

So, from circuit diagram-1(b),

$$\begin{aligned} V_{in,max} &= \left(I_{Z,max} + \frac{V_Z}{R_L}\right) R_S + V_Z \\ &= \left(0.0833 + \frac{6}{2 \times 10^3}\right) \times 200 + 6 \\ V_{in,max} &\approx 23\ V \end{aligned}$$

Similarly, for $V_{in,min}$, from circuit diagram-1(b),

$$\begin{aligned} V_{in,min} &= \left(I_{Z,min} + \frac{V_Z}{R_L}\right) R_S + V_Z \\ &= \left(2 \times 10^{-3} + \frac{6}{2 \times 10^3}\right) \times 200 + 6 \\ V_{in,max} &= 7\ V \end{aligned}$$

Therefore range of variation of V_{in} for which Zener can be used safely to produce fixed output voltage across load is $7\ V < V_{in} < 23\ V$.