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Zener Diode Selection For Faster Inductor Reset in Solenoid Circuits

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A previous article discussed how use of a Zener diode in series with the recuperating diode speeds up operation of a solenoid driver circuit (see the reference). That article proposed a new driver circuit configuration to reduce the Zener diode's power dissipation by bypassing it when it is not aiding in reset of the solenoid's inductor.

However, that article also demonstrated the underlying concept that adding a voltage-dropping component in the path of the inductor core's magnetic state recuperating current can shorten the core's magnetic state recuperation process by means of stored energy dissipation. This concept, which might also be beneficial for operation of power electronics circuits that use energy-storing inductors, was demonstrated by way of an LTSPICE simulation of the solenoid control circuit.

This article continues the discussion by offering an analysis of the dissipation of energy stored in the inductor's magnetic core and how the Zener diode shortens the magnetic core recuperation process. The purpose here is to provide formulas and plots that facilitate the Zener diode selection necessary for reducing the energy dissipation time by a user-defined factor. As we'll see, that factor will be a fraction of the recuperation time when only a conventional silicon recuperating diode is present. Fig. 1 depicts a partial schematic diagram of the solenoid L_s control circuit, with Zener diode Z inserted in the recuperating current path.

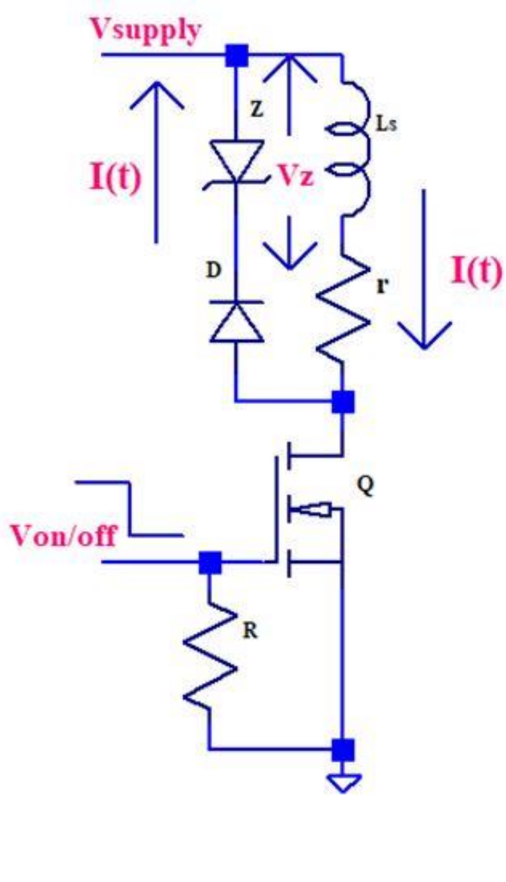

Fig. 1. Zener diode Z defines how quickly inductance L_s demagnetizes.

Circuit Analysis

When MOSFET Q turns off, recuperating current I(t) keeps flowing in the circle composed of solenoid inductance L_S, solenoid winding resistance r, diode D and Zener diode Z. For this circuit, the following relationship holds true:

$$L_S \cdot \left(\frac{d}{dt} I(t) \right) = -r \cdot I(t) - V_Z \qquad (1)$$

Dividing by L_S and collecting the terms on the left side of the equation, we obtain:

$$\frac{d}{dt} I(t) + \frac{r}{L_S} \cdot I(t) + \frac{V_Z}{L_S} = 0 \qquad (2)$$

Taking the Laplace transform of equation (2) brings this equation into the s-domain:

$$\frac{d}{dt} I(t) + \frac{r}{L_S} \cdot I(t) + \frac{V_Z}{L_S} \text{ laplace } \rightarrow \frac{V_Z + r \cdot s \cdot \text{laplace}(I(t), t, s) + L_S \cdot s^2 \cdot \text{laplace}(I(t), t, s) - L_S \cdot s \cdot I(0)}{L_S \cdot s}$$

which simplifies to

$$s \cdot I(s) - I_0 + \frac{V_Z}{s \cdot L_S} + \frac{r}{L_S} \cdot I(s) = 0 \qquad (3)$$

where current I_0 is the initial condition that emerges when solving the differential equation and physically is the current that flowed through the inductor before it was interrupted.

Solving for I(s), first we get

$$I(s) \cdot \left(s + \frac{r}{L_S} \right) = I_0 - \frac{V_Z}{s \cdot L_S} \qquad (4)$$

which leads to the expression for the current Laplace transform,

$$I(s) = \frac{I_0 - \frac{V_Z}{s \cdot L_S}}{s + \frac{r}{L_S}} \qquad (5)$$

Reverting to the time domain, by taking the reverse Laplace transform of (5), yields

$$\frac{I_0 - \frac{V_Z}{s \cdot L_s}}{s + \frac{r}{L_s}} \;\Bigg|\; \begin{array}{l} \text{invlaplace} \\ \text{assume}, s > 0 \end{array} \rightarrow \frac{V_Z \cdot e^{-\frac{r \cdot t}{L_s}} - V_Z + I_0 \cdot r \cdot e^{-\frac{r \cdot t}{L_s}}}{r}$$

which gives us an expression for the recuperating current as a function of the Zener diode voltage:

$$I(t) = \frac{V_Z \cdot e^{-\frac{r \cdot t}{L_s}} - V_Z + I_0 \cdot r \cdot e^{-\frac{r \cdot t}{L_s}}}{r} \qquad (6)$$

Now, we can define how much time it takes to completely reset the magnetic core. It is magnetically restored, or reset, when current I(t) decays down to zero. Designate this time as $T = t_0$, we begin by setting equation (6) to zero:

$$\frac{V_Z \cdot e^{-\frac{r \cdot t}{L_s}} - V_Z + I_0 \cdot r \cdot e^{-\frac{r \cdot t}{L_s}}}{r} = 0 \qquad (7)$$

Solving (7) for t, we get

$$t_0\left(V_Z\right) = -\frac{L_s \cdot \ln\left(\frac{V_Z}{V_Z + I_0 \cdot r}\right)}{r} \qquad (8)$$

So, equation (8) defines the time necessary for full reset of the magnetic core. Using formula (8), we can also easily define the required Zener diode voltage to ensure a given reset time:

$$V_Z\left(t_0\right) = -\frac{I_0 \cdot r \cdot e^{-\frac{r \cdot t_0}{L_s}}}{e^{-\frac{r \cdot t_0}{L_s}} - 1} \qquad (9)$$

There may be cases where equation (9) is sufficient to obtain a target value of Zener voltage. However, as we'll see there are some additional equations that can be helpful.

We have to mention here that function (6) extends to negative values for I(t), which is physically impossible, and should be limited to the 0 value at t_0:

$$I(t) = \begin{pmatrix} \left| \begin{array}{l} \dfrac{V_Z \cdot e^{-\frac{r \cdot t}{L_S}} - V_Z + I_0 \cdot r \cdot e^{-\frac{r \cdot t}{L_S}}}{r} \\ 0 \quad \text{if} \quad t > t_0(V_Z) \end{array} \right. \end{pmatrix} \tag{10}$$

Typically, a Zener diode is not used in the solenoid reset circuit such that the magnetic core reset time is at its maximum, as determined by the silicon diode. In this case we can replace V_Z with the voltage drop across a regular Si diode V_D, which can be assumed constant. Let's designate this reference reset time as t_{ref}.

$$t_{ref} = -\frac{L_S \cdot \ln\left(\dfrac{V_D}{V_D + I_0 \cdot r}\right)}{r} \tag{11}$$

In this case we can talk about solving a problem: what Zener diode do we have to put into the circuit in series with the regular diode in order to shorten the magnetic core reset process by some number of times, say γ times, which we will call the shortening coefficient. This shortening coefficient depends on the Zener diode voltage:

$$\gamma\left(V_Z\right) = \frac{t_0}{t_{ref}} \tag{12}$$

$$\gamma\left(V_Z\right) = \frac{\ln\left(\dfrac{V_Z}{V_Z + I_0 \cdot r}\right)}{\ln\left(\dfrac{V_D}{V_D + I_0 \cdot r}\right)} \tag{13}$$

As we will see, the equations derived above for $t_0(V_Z)$ and $\gamma(V_Z)$ can be plotted to facilitate selection of the zener diode, for which voltage is the first parameter that guides diode selection.

Zener Diode Power Dissipation

In addition to determining the required Zener diode voltage, diode selection also requires determining its necessary power rating. We can use the familiar equation for diode power dissipation,

$$P_{diss\_Z}\left(V_Z\right) = \frac{1}{t_0\left(V_Z\right)} \cdot \int_0^{t_0\left(V_Z\right)} I(t) \cdot V_Z \, dt \tag{14}$$

Zener Diode Energy Dissipation

In addition to knowing the power dissipated by the Zener, it is valuable to know the energy dissipated by the Zener. The following equation will help us to determine how our choice of Zener voltage affects circuit losses.

$$E_{diss\_Z}(V_Z) := \int_0^{t_0(V_Z)} I(t) \cdot V_Z \, dt \qquad (15)$$

A Design Example

Let's assign some component values to our solenoid driver circuit (repeated here in Fig. 2) to illustrate how we apply the equations derived above in an actual circuit design. Our goal in this section is not to identify a specific Zener diode voltage for a predetermined reset time, but rather to illustrate how to quantify the relationships between Zener diode voltage and reset time and Zener power rating, so that designers can choose the Zener voltage value to achieve the desired reduction in reset time. We'll also quantify the relationship between Zener diode voltage and energy dissipation to determine how Zener diode selection impacts circuit losses.

To begin, let's set r = 0.06 Ω , L_S = 2400 µH, I_0 = 2 A and V_D = 0.6 V.

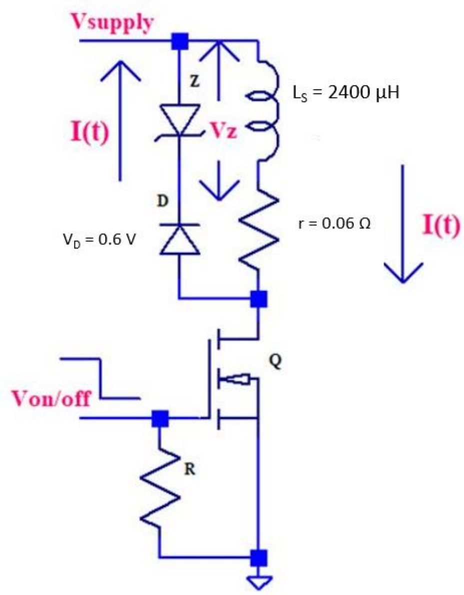

Fig. 2. Example solenoid driver circuit with values assigned to components in the reset circuit for the purpose of determining V_Z based on the desired reset time.

Reset Time

As determined above in equation (8), reset time is a function of the Zener diode voltage, the current at turn-off of the MOSFET, and the solenoid winding resistance:

$$t_0(V_Z) := -\frac{L_S \cdot \ln\left(\frac{V_Z}{V_Z + I_0 \cdot r}\right)}{r}$$

Applying our example circuit conditions, we can plot reset time as a function of the Zener diode voltage.

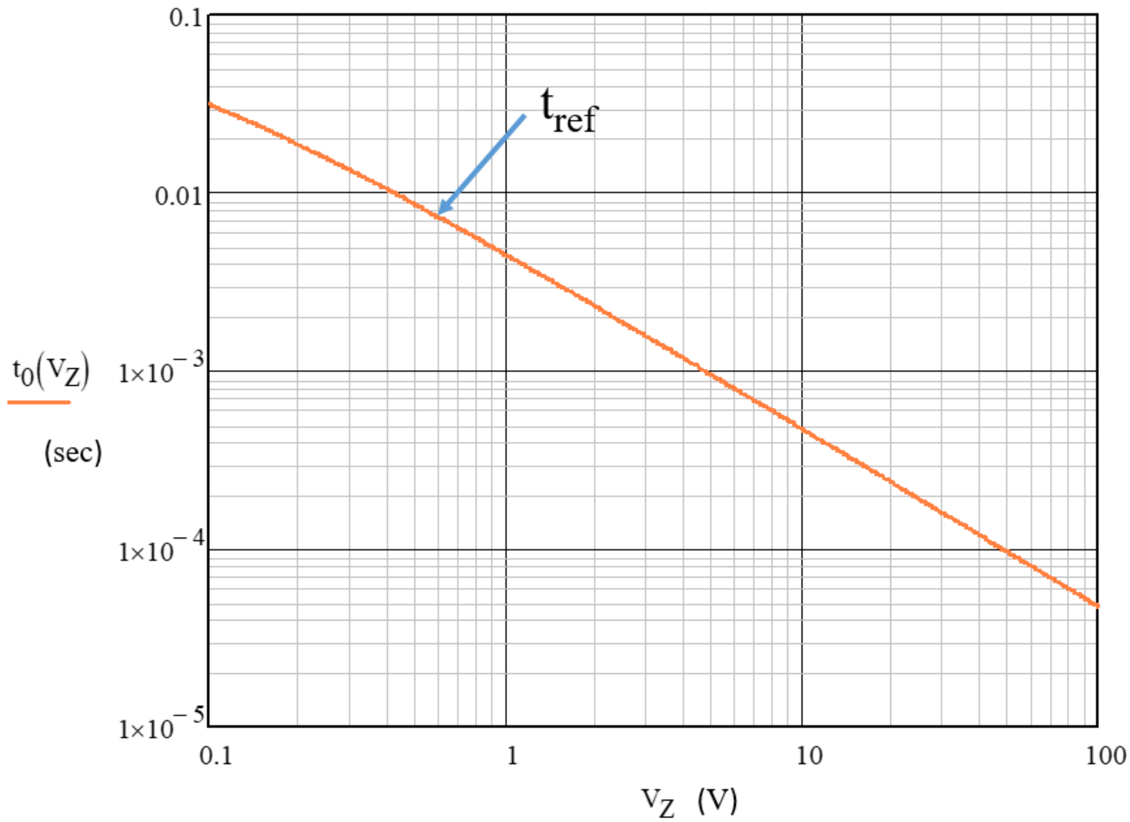

Fig. 3. Inductor demagnetizing time drops with the increase in Zener diode voltage. From this graph, we can also determine the reset time for the case where no Zener is used. The t_{ref} shown here is for an example silicon diode with a forward voltage of 0.6 V.

Shortening Coefficient

From equation (13) we know that the reset time can be shorted by a factor of γ:

$$\gamma\left(V_Z\right) := \frac{\ln\left(\frac{V_Z}{V_Z + I_0 \cdot r}\right)}{\ln\left(\frac{V_D}{V_D + I_0 \cdot r}\right)}$$

which we can plot as a function of Zener diode voltage:

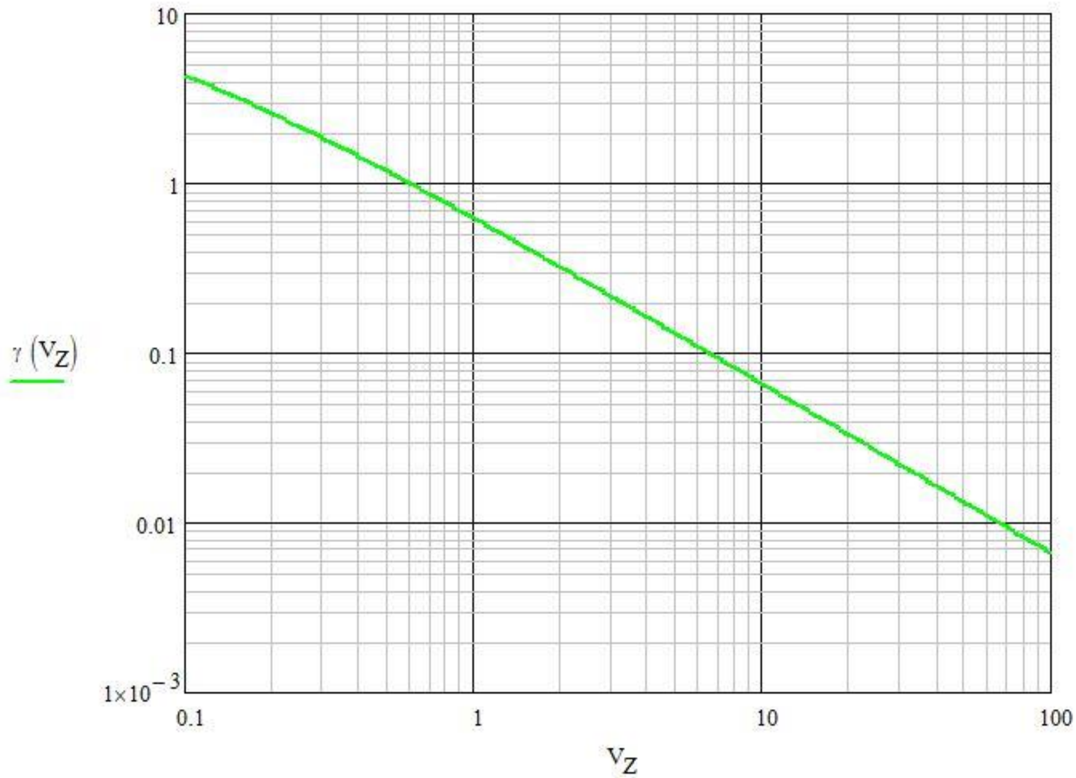

Fig. 4. The shortening coefficient drops with the Zener diode voltage increase.

For our design example, knowing the reset time, t_{ref}, from Fig. 3, we can use the Fig. 4 graph of $\gamma(V_Z)$ to select a value of Zener diode voltage that provides the desired reduction in reset time. However, this graph won't get us to the exact value of Zener diode voltage because in general we will have to select the Zener diode voltage from the standard voltage values that are available for Zeners. However, Fig. 4 helps the designer to select an approximate value of γ for diode selection.

Zener Diode Power Dissipation

To determine the required power rating of the Zener diode, we recall equation (13):

$$P_{diss\_Z}(V_Z) := \frac{1}{t_0(V_Z)} \cdot \int_0^{t_0(V_Z)} \left| \begin{array}{l} \dfrac{V_Z \cdot e^{-\frac{r \cdot t}{L_S}} - V_Z + I_0 \cdot r \cdot e^{-\frac{r \cdot t}{L_S}}}{r} \\ 0 \quad \text{if} \quad t > t_0(V_Z) \end{array} \right. \cdot V_Z \, dt$$

Plugging in values of r and L_S from our example, and calculating values of t_0 for the range of Zener diode voltages, we can plot instantaneous power dissipation as a function of Zener diode voltage as shown in Fig. 5.

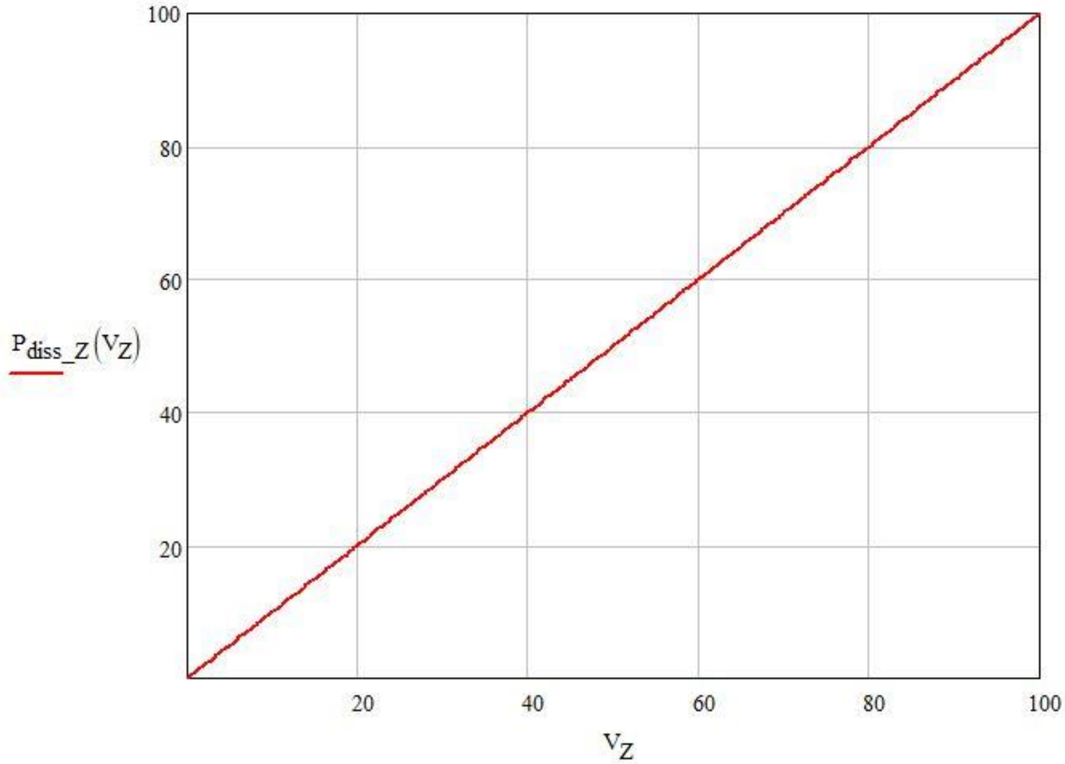

Fig. 5. Instantaneous power dissipation of the Zener diode goes up with increasing Zener voltage. Meanwhile as Zener voltage rises, the length of time during which the Zener diode conducts goes down, making the energy dissipated by the Zener diode practically constant.

The graph in Fig. 5 is not meant as a guideline for specifying a power rating for the Zener diode—it's more of a starting point in understanding what the limit of this power dissipation will be and how this limit varies with Zener voltage. Graph 5 shows instantaneous power without respect to reset time.

Meanwhile, equation 14 gives us an equation for power dissipation during a single reset pulse. That value also is insufficient for rating the diode. The actual power rating needed will depend on operating conditions in the solenoid circuit. Both the frequency and duty cycle of pulses seen by the Zener diode must be considered.

Zener Diode Energy Dissipation

Recalling equation (14),

$$E_{diss\_Z}(V_Z) := \int_0^{t_0(V_Z)} \left| \begin{array}{l} \dfrac{V_Z \cdot e^{-\frac{r \cdot t}{L_s}} - V_Z + I_0 \cdot r \cdot e^{-\frac{r \cdot t}{L_s}}}{r} \\ 0 \quad \text{if} \quad t > t_0(V_Z) \end{array} \right. \cdot V_Z \, dt$$

we can plot the energy dissipated by the Zener as a function of Zener voltage as shown in Fig. 6. The result here tells us that the energy dissipation and therefore the power losses associated with use of the Zener do not vary much with Zener voltage—confirming our observation above about energy dissipation remaining constant.

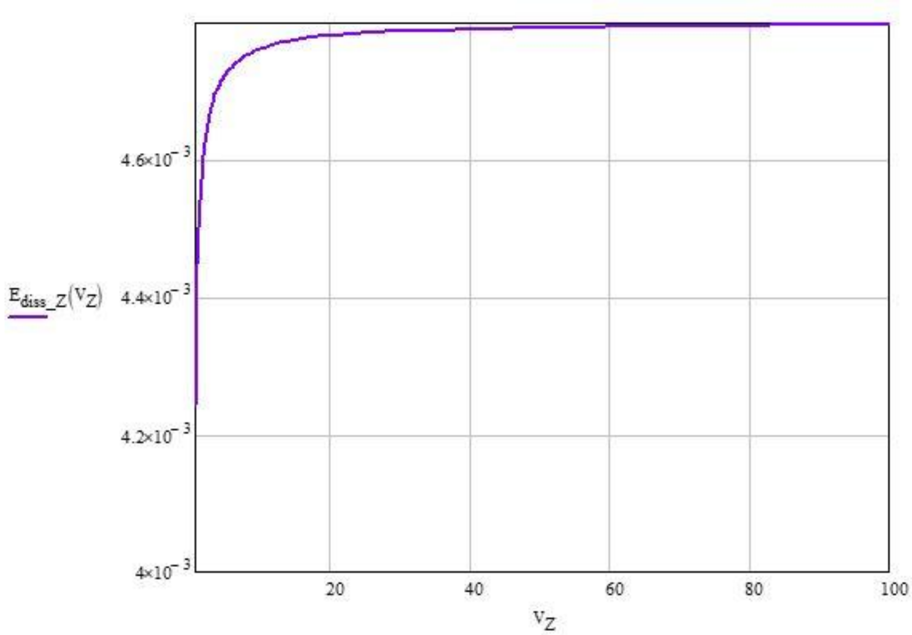

Fig. 6. Zener diode energy dissipation (plotted here in joules) is nearly independent of Zener voltage (plotted here in volts).

Recuperation Current

Having plotted the general relationships between Zener voltage and reset time, now we will quantify the relationship between reset time and Zener voltage for practical values of Zener voltage while also observing how fast the recuperation current decreases based on these values.

The rate of change for the reset current is worth observing for two reasons. First, it affects the rating of the Zener diode. The faster the recuperation current is changing, the less it impacts the diode thermally and the higher the power dissipation the Zener can tolerate. Secondly, a customer may actually specify a value for this rate.

The following five values are representative of the range of commonly available Zener devices.

$$V_Z := \begin{pmatrix} 4.7 \\ 6.8 \\ 12 \\ 33 \\ 82 \end{pmatrix} V$$

To plot the recuperation current versus these Zener values, we return to equation 6

$$I(t) := \overrightarrow{\frac{V_Z \cdot e^{-\frac{r \cdot t}{L_S}} - V_Z + I_0 \cdot r \cdot e^{-\frac{r \cdot t}{L_S}}}{r}}$$

which leads to the plots in Fig. 7. As the graph shows, recuperation current decreases at a much faster rate at higher values of Zener voltage.

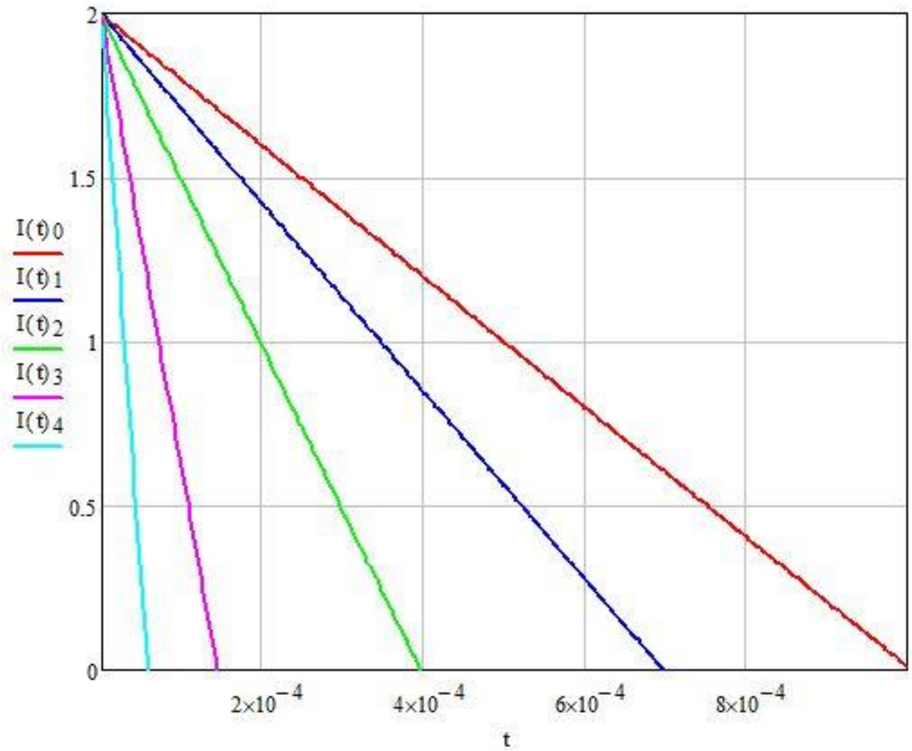

Fig. 7. Solenoid recuperation current drops faster if Zener voltage is higher.

Conclusions

From the calculations presented above, there are several takeaways. First, the inductor recuperation (reset) time strongly depends on the aggregate voltage drop (i.e. the Zener voltage drop) in the recuperation current path: the higher the voltage drop, the shorter the recuperation time. Secondly, the shortening coefficient allows for easily defining what Zener diode to select to provide the desired reset time. Although we can always calculate a Zener voltage value for a given reset time without regard to the shortening coefficient, the shortening coefficient is a convenient tool, especially for the case where a customer requests a specific x-times reduction in the reset time.

As we also seen from our example, the Zener diode power dissipation grows as the reset time gets shorter (which corresponds to increasing Zener voltage). However, the actual power rating that will be required for the Zener diode will depend on the specific pulse characteristics seen by diode and on diode thermal resistance. The frequency and duty cycle of the pulses will need to be considered.

On the other hand, the energy dissipated by the Zener diode during the reset time does not practically depend on the Zener diode voltage. Rather, this energy dissipation depends on the inductor operating current and coil resistance only. So the designer's choice of reset time or Zener diode voltage will not affect losses within the Zener.

Finally, recuperation (reset) current decays faster at higher Zener voltage, so it is recommended to use Zener diodes with the highest operating voltage possible to make the reset time shortest, enabling the fastest solenoid operation.

Reference

"Fast, Simple Solenoid Driver Saves Power In Industrial Applications" by Gregory Mirsky, How2Power Today, February 2017.

About The Author

Gregory Mirsky is a design engineer working in Deer Park, Ill. He currently performs design verification on various projects, designs and implements new methods of electronic circuit analysis, and runs workshops on MathCAD 15 usage for circuit design and verification. He obtained a Ph.D. degree in physics and mathematics from the Moscow State Pedagogical University, Russia. During his graduate work, Gregory designed hardware for the high-resolution spectrometer for research of highly compensated semiconductors and high-temperature superconductors. He also holds an MS degree from the Baltic State Technical University, St. Petersburg, Russia where he majored in missile and aircraft electronic systems.

Gregory holds numerous patents and publications in technical and scientific magazines in Great Britain, Russia and the United States. Outside of work, Gregory's hobby is traveling, which is associated with his wife's business as a tour operator, and he publishes movies and pictures about his travels online.