# How to Calculate Power Losses in Gen 5 Diodes

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## INTRODUCTION

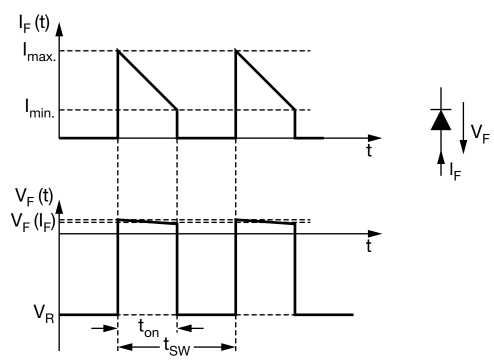
The aim of this application note is to explain a simple procedure for evaluating power losses in Gen 5 diodes.

Our family of Gen 5 diodes consists of ultrafast devices with breakdown voltages of 600 V and 1200 V that are designed to deliver the highest efficiency in high frequency switching circuits. In these circuits, the diodes work in two conditions: forward and reverse.

In the forward condition, diodes carry the current while showing the lowest resistance at the current flow (ON state) and the lowest possible voltage anode to cathode.

In the reverse condition, the voltage anode to cathode across the diode is negative (OFF state) and the device is like an open circuit; the current flowing through the diode - the leakage current - is very small.

Fig. 1 shows the visible voltage and current in a typical working condition for a diode in a switching circuit, such as a buck converter.




$t_{SW}$ switching period = $1/f_{SW}$

$t_{on}$ ON time, diode is in forward

$t_{SW} - t_{on}$ OFF time diode is in reverse (CCM mode)

$d = \frac{t_{on}}{t_{SW}}$ duty cycle

$I_F$ diode current forward current positive reverse current negative leakage

$V_F$ diode voltage positive anode to cathode

Fig. 1 - Diode Current

The transition between the forward and reverse conditions is called recovery. Forward recovery is when a diode goes from the OFF state to the ON state. Reverse recovery is when a diode goes from the ON state to the OFF state. These transitions are associated with losses, known as switching losses. Usually, forward recovery losses are negligible; but reverse recovery losses - particularly those in high frequency circuits - can be a non-negligible portion of losses present in the diode.

This application note focuses on losses present during the forward and reverse conditions, not those related to the state change (switching losses). Switching losses are strongly dependent on diode working conditions, reverse voltage, di/dt, the inductance and a number of external factors, like the active switch and how the switch is driven.

A separate analysis is often only possible on real circuits, because during the design phase stray inductances are not well known. So, the analysis should be performed on prototypes or very detailed models. Conduction losses can be evaluated with high accuracy using the below model and procedure. It should be taken into account that Gen 5 diodes are available in two speeds: H and X. Both devices are ultrafast, but the H series is optimized for conduction losses and the X series is optimized for switching losses. This means that forward voltage and related conduction losses are different for the two devices. Selecting the right diode speed can be a matter of balancing losses, i.e. when conduction and switching losses are in the same order of magnitude or their sum is minimized.

The total losses are key for choosing a device. Both series are able to switch with high di/dt at high voltage and temperature, but it is the amount of losses related to switching frequency that define which speed is right.

# How to Calculate Power Losses in Gen 5 Diodes

This application note focuses on conduction losses that are related to the voltage across the diode.

In every condition, conduction losses for the H series are lower than the X series, but switching losses are different and their contribution should be added to conduction losses to understand if the total losses are minimized with an H speed or X speed device during the forward state and leakage current during the reverse state. The ideal diode has a forward voltage of 0 V and reverse current of 0 A. A real device has a certain voltage anode to cathode that changes as a function of current and temperature when it is ON, and leakage that changes as a function of reverse voltage and temperature when it is OFF. The product voltage times current gives instantaneous power across the diode, whether ON or OFF. The average power dissipated in the diode could be summarize in Formula 1.1

**1.1**

$$P_{DAVG} = V_F \times I_F \times \frac{t_{on}}{t_{SW}} + V_R \times I_R \times \frac{t_{off}}{t_{SW}}$$

where $V_F$ is the forward voltage when the diode is ON and the current flow is $I_F$. $I_R$ is the current through the diode when the reverse voltage is $V_R$. The weighted average gives the dissipated power in the diode. In a periodic condition $t_{on}$ is time when the diode is ON and $t_{off}$ is time when the diode is OFF. $t_{SW}$ is the period of the cycle that could be different from the sum of $t_{on}$ and $t_{off}$. When the diode is not ON or OFF, it is in idle and very small reverse losses or no losses are related to this phase.

The difference between the forward and reverse conditions is that in the forward condition, the voltage across the diode is small and the current could be large. During the reverse condition, the voltage could be around 80 % of the rated voltage, but the leakage current is extremely small.

## BEHAVIOR OF DIODE FORWARD VOLTAGE

A large portion of dissipated power is related to the forward voltage drop, so understanding the behavior of the anode to cathode voltage drop helps in understanding the model for the losses calculation. The forward voltage of Gen 5 600 V and 1200 V diodes is plotted in Fig. 2 and Fig. 3.

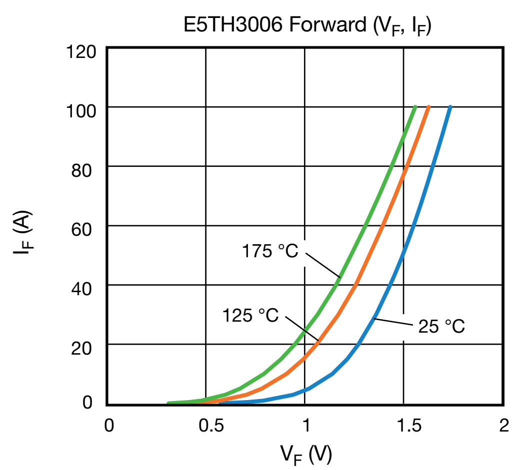



Fig. 2 - Forward Current Characteristics for the 30 A, 600 V, E5TH3006

# How to Calculate Power Losses in Gen 5 Diodes

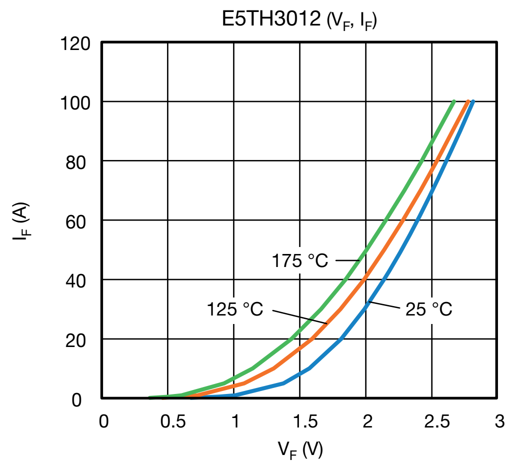



Fig. 3 - Forward Current Characteristics for the 30 A, 1200 V, E5TH3012

It can be seen that the forward voltage drop is mainly a function of current and temperature in the junction. The relationship between current and forward voltage for a simple PN junction is

**1.2**

$$i_D = I_S(T)\left(e^{\left(\frac{qV_D}{nkT}\right)} - 1\right) = I_S(T)\left(e^{\left(\frac{V_D}{nV_T}\right)} - 1\right) \text{ with } I_S(T) = q_e A N_i^2\left(\frac{1}{N_D(T)} \times \sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_A(T)} \times \sqrt{\frac{D_n}{\tau_n}}\right)$$

Formula 1.2 (the Shockley equation) is a good model for diodes built with a PN junction with step symmetrical doping, like in Fig. 4.

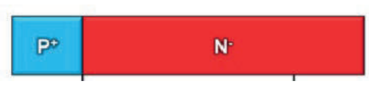



Fig. 4 - Simple PN Junction

This kind of structure works fine for diodes with low breakdown voltage. For devices with a breakdown voltage of 600 V or 1200 V another structure is required: the PiN junction, as shown in Fig. 5.


Fig. 5 - High Voltage Device PiN Junction

Between the P and N doped zones, the PiN junction has a layer with a low doping concentration, which helps to redistribute the electric field and reduce its strength, despite the high voltage.

The intrinsic layer helps to achieve better characteristics in the reverse condition. However, it also inserts a series resistance and other losses to obtain ultrafast recovery that are not taken into account in Formula 1.2.

A reasonable model for forward voltage behavior - quite common for a thyristor but also very good for a diode - is the ABCD model.

**1.3** $V_F = A + B\ln(I_F) + CI_F + D\sqrt{I_F}$

# How to Calculate Power Losses in Gen 5 Diodes

Equation 1.3 gives the forward voltage of the diode as a function of current. From a physical point of view, the meaning of each term could be written as

**1.4** $$V_F = A + \frac{n}{\frac{q}{kT}} \ln\left(\frac{I_F}{I_s}\right) + R_{T0} I_F + D\sqrt{I_F}$$

where

A is the threshold voltage and

B terms derive from approximate solution of equation 1.2

$$I(V) = I_S\left(\exp\left(\frac{qV}{nkT}\right) - 1\right) \rightarrow V(I) \approx \frac{1}{\frac{q}{nkT}} \ln\left(\frac{I}{I_S}\right) \rightarrow V(I) = \frac{1}{\frac{q}{nkT}}(\ln(I) - \ln(I_S)) \rightarrow \frac{1}{\frac{q}{nkT}} \ln(I)$$

B is $\frac{1}{\frac{q}{nkT}}$

and it change in the function of the technology (Si, Ge, SiC, GaN...). Due to these approximations, the model cannot work at zero current or very small current (usually lower than 1/50 of rated current). In a real application a current lower than 1/50 of the rated current does not contribute to total losses. If the device is working with a larger current than 10 x $I_S$, as is common in real applications, the formula 1.3 is a good model.

C is the $R_{t0}$, the term that takes in account the series resistance of the diode.

D is a coefficient that improve the accuracy of curve fit at current level around the middle of rated current.

With a real device, the coefficients ABCD are evaluated from the typical forward voltage curve (the typical device is the average of many measurements). The coefficients ABCD are the best fit for the forward voltage curve.

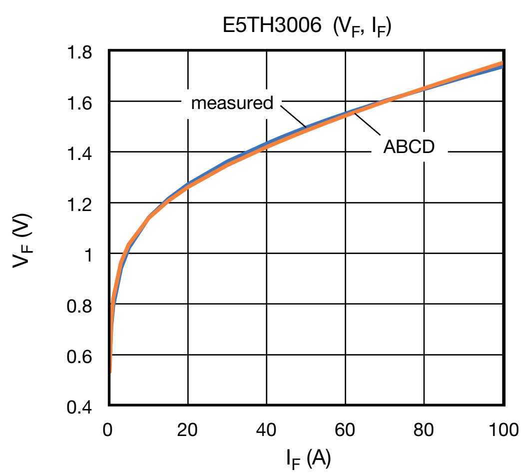



Fig. 6 - The Forward Voltage as a Function of Current for a Typical E5TH3006, Measured and Simulated

From the graph in Fig. 6, the model seems to be accurate for a current higher than 1/10 of the rated current (for a lower current, it shows small differences like other models, such as SPICE), and follows quite well the behavior of forward voltage at high current. This is required because Gen 5 diodes could switch at a current that is three times the rated current and the limit is substantially thermal, this is important to estimate the losses in a working condition with a high crest factor that has high power dissipated associated.

# How to Calculate Power Losses in Gen 5 Diodes

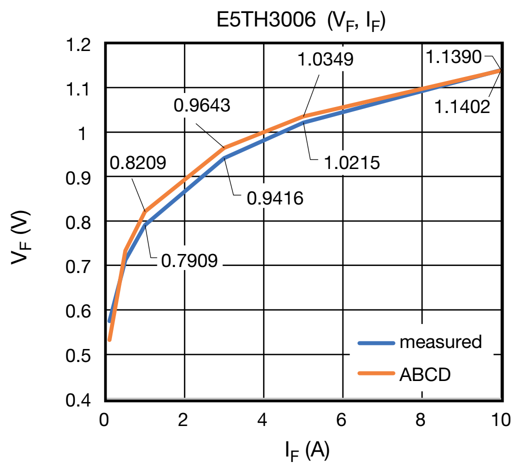



Fig. 7 - The Forward Voltage as a Function of Current for a Typical E5TH3006, Measured and Simulated at Low Current

In Fig. 7 there is a magnification of Fig. 6, in which it is possible see the behavior of the measurement modeled at a low current. The lower limit is 0.1 A because Formula 1.3 cannot accept current values around 0 A, as opposed to formula 1.2, where 0 V means 0 A in the diode. For a practical evaluation of power losses, the range of most interest is well covered by formula 1.3, and the very low current value can be neglected.

To evaluate the losses, if the current through the diode is DC or rectangular, formula 1.3 is very precise, but the real application has different characteristics.

1. The current in a real application usually has a shape different from the DC or perfectly rectangular waveform
2. The diode through which the current flows gets hot and ABCD parameters change

From Fig. 2 and Fig. 3, it is clear that the $T_j$ temperature is an important factor for the evaluation of power dissipated in the diode, because it has an influence on the forward voltage and leakage current.

To take the effects of temperature into account, it is necessary to add at the four ABCD parameters another set of (coefficient ka, kb, kc, kd) data that describes the behavior of the ABCD parameters with temperature.

**1.5** $$V_F(I_F) = A(1 + ka(T_j - 25)) + B(1 + kb(T_j - 25)) \times \ln(I_F) + C(1 + kc(T_j - 25)) \times I_F + D(1 + kd(T_j - 25)) \times \sqrt{I_F}$$

Formula 1.5 could be a simple model of forward voltage as a function of temperature if the ABCD coefficients are linear with the temperature.

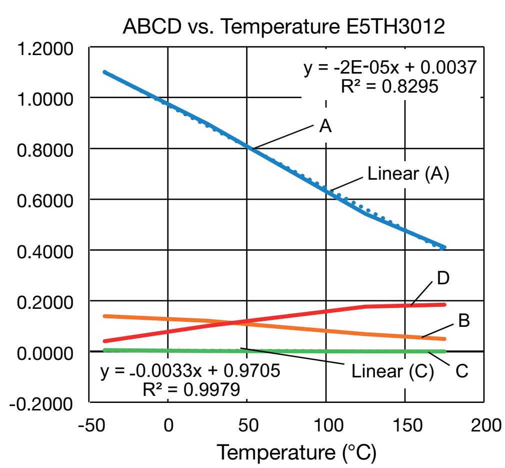



Fig. 8 - Behavior as a Function of the Temperature of ABCD Coefficients

**Note**

- ka, kb, kc, kd, represent the behavior of parameters ABCD with temperature

# How to Calculate Power Losses in Gen 5 Diodes

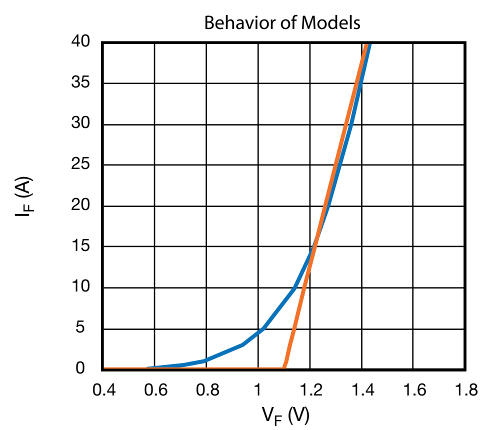
This approach is not general and the variation of the ABCD parameters could be very non-linear. In this case, the Gen 5 diode is developed to minimize the effect of temperature on series resistance, so a 1° order model is enough to obtain an accurate result. Other technology can have completely different behavior with temperature and formula 1.5 will give a poor result. This behavior of Gen 5 diodes is obtained with a special thin wafer technology that minimizes the effect of resistance variation with temperature. This characteristic is visible in the forward voltage curve in Fig. 2 and Fig. 3, where the slope of the $V_F$ curve is quite constant with temperature ($V_F$ curves at high current are parallel) and the temperature coefficient kc of the C parameter is very small.

The temperature only has the ability to affect the threshold voltage, as is visible from the thermal coefficient ka of the A parameter. This is good for thermal stability because increasing the temperature decrease the losses. This characteristic only requires precautions when many devices are used in parallel. Usually, if devices are from the same lot, using two or more in parallel is enough a good thermal coupling (all devices should be mounted on the same heatsink) and the current path should be symmetrical. These simple precautions are enough for a good current share.

A minimum of eight parameters are required to do the evaluation of forward voltage, and if the current has a shape different from the DC or rectangular, is necessary to repeat the evaluation of forward voltage for each value of current, point by point.

This approach would be good for a simulator, but for a preliminary evaluation like the choice of a device, it is more practical to use the piecewise approach.

The forward voltage curve of a diode could be approximated with the piecewise method:



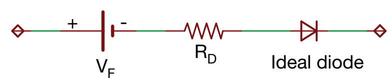




Fig. 9 - Forward Voltage of a Real Diode and Piecewise Model

The electrical equivalent circuit of the piecewise model is shown in Fig. 9, and with this network the evaluation of losses becomes quite simple and is enough to apply Formula 1.6:

**1.6** $P_D = V_{T0} \times Id_{AVG} + R_D \times Id^2{}_{RMS}$

Diode average current and RMS current are easy to evaluate for many current waveforms (see Figure A) or from any simulation in which it is simple to obtain the average and RMS value of the current in the device. Usually, it's simple do a simulation with an ideal diode, and after evaluating the losses in the diode, using the average and RMS value of the simulated current. Usually, an ideal rectifier or real diode model in a power circuit doesn't change the simulation result much. If this happens, it means that losses in the diode are not negligible and usually are not the desiderata in high efficiency circuitry.

$V_{TO}$ and $R_D$ are two parameters that are related to coefficients A and C, and from a numerical point of view they are similar. Often $V_{T0}$ and $R_D$ are confused with $V_d$ and $r_d$, which are the parameters for small-signal diodes. $r_d$ (dynamic resistance) is defined as the tangent to the forward voltage curve, while $V_d$ is the cross of the $r_d$ line with the abscissa axis. For power applications, instead of a tangent the slope of a straight line between two points on the forward voltage curve is often used, which corresponds to a current range where the device could work. These different approaches are shown in Fig. 10.

# How to Calculate Power Losses in Gen 5 Diodes

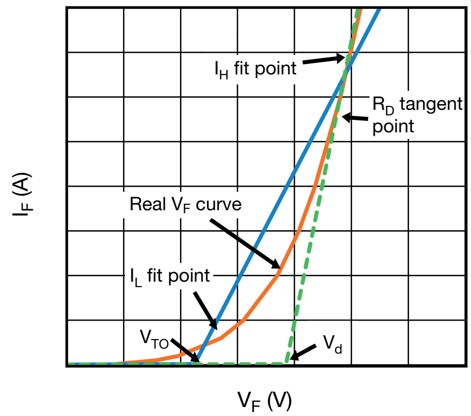



Fig. 10 - Differences Between the Small Signal and Wide Range Approaches

The $r_d$ is a tangent point on the $V_F$ curve because in theory we are using this model for a small signal, and the current running through the device doesn't change much. In a power circuit the current level could be very different, so evaluate the $R_D$ as an intercept point on a certain range gives a more accurate result.

The $V_{T0}$ and $R_D$ given for Gen 5 diodes are evaluated as coefficients to fit the power losses. The coefficients lose physical meaning and become two parameters for evaluating the power dissipated in the diode.

The procedure for obtaining $V_{T0}$ and $R_D$ (sometimes called $R_{T0}$ when it is referred to in the context of a thyristor) is based on an accurate evaluation of power losses in the diode, using the forward voltage across the diode as the model for Formula 1.3. The power losses are calculated point by point on the current waveform (like in SPICE simulations).

At the same time the average current value and the RMS current value are calculated on the current waveform.

Doing this for different current level and shapes, and having the avg current and the RMS value $V_{TO}$ and $R_D$ are evaluated as the best fit that give the same power calculated with Formula 1.6 and the simulation based on Formula 1.3.

The obtained model of $V_{T0}$ and $R_D$ is valid at certain $T_j$ considered constant during simulation and in the range of current used to evaluate the power.

In Fig. 1 and Fig. 2, the variation of forward voltage with temperature is visible. For normal applications, the $T_j$ could go from 25 °C to 125 °C, but the device could also be used in a more stressful condition from -40 °C to +175 °C, so it is not possible to neglect the effect of temperature on the diode's characteristics. It is possible to extend Formula 1.6 as a function of temperature by adding temperature coefficients ($K_V$ and $K_R$) for $V_{T0}$ and $R_D$.

**1.7**
$$V_{T0}\,(T_j) = k_V \times (T_j - 25) + V_{T0}\,(25\ °C)$$

$$R_D\,(T_j) = k_R \times (T_j - 25) + R_D\,(25\ °C)$$

With $V_{T0}$ and $R_D$ as a function of temperature, it is possible to iterate the evaluation of dissipated power at junction temperature obtained at the previous step and update $V_{T0}$ and $R_D$ to evaluate the power with the new $T_j$, as show in Fig. 11.

# How to Calculate Power Losses in Gen 5 Diodes

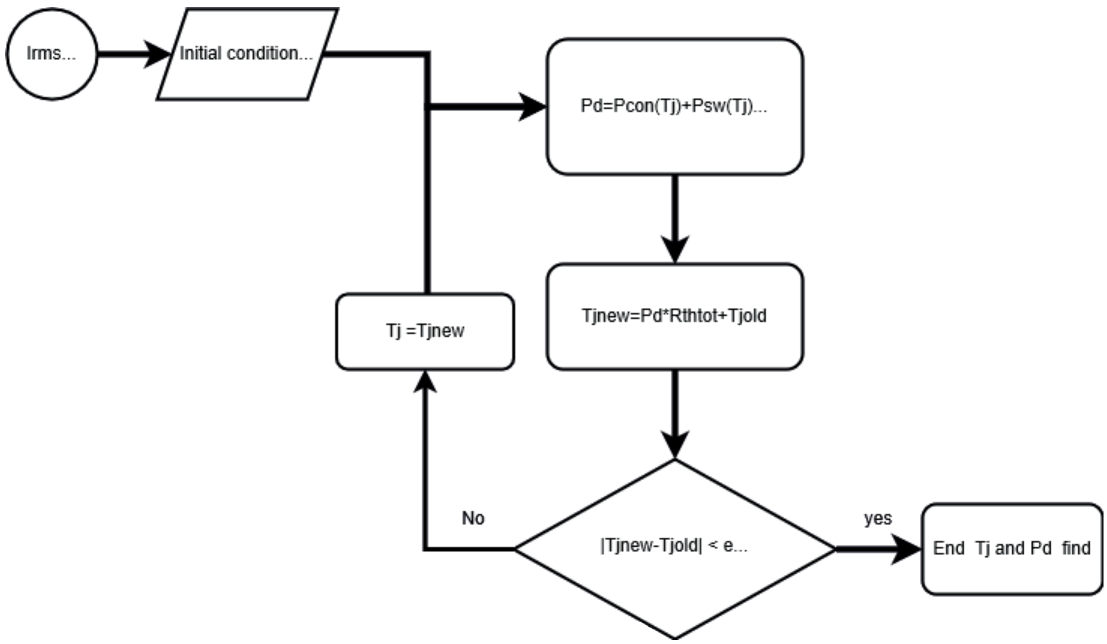



Fig. 11 - $T_j$ and Power Losses Evaluation Flow Chart

Note that the SPICE simulation of the diode could be done at a certain $T_j$, but it is fixed during the simulation. Only a different simulator (usually an event-based simulator) can take the effect of temperature during simulation into account. Doing this in SPICE requires the implementation of a thermo electrical model separated from the native SPICE model of the diode.

# How to Calculate Power Losses in Gen 5 Diodes

The coefficients for different devices are in the following table:

**TABLE 1**

| $I_{F(AV)}$ (A) | DEVICE | PACKAGE | $V_F$ at $I_F$ (V) | $t_{rr}$ (ns) | $V_{TO}$ (25 °C) (V) | $R_D$ (25 °C) (Ω) | $k_V$ (°C$^{-1}$) | $k_R$ (°C$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 15 | VS-E5TH1506-M3 | TO-220AC | 1.15 | 31 | 0.8437 | 0.0334 | -0.002182 | 0.00002524 |
| 15 | VS-E5TH1506S2LHM3 | $D^2$PAK 2L (TO-263AB 2L) | 1.15 | 31 | 0.8437 | 0.0334 | -0.002182 | 0.00002524 |
| 15 | VS-E5TH1506THN3 | TO-220AC | 1.15 | 31 | 0.8437 | 0.0334 | -0.002182 | 0.00002524 |
| 15 | VS-E5TX1506-M3 | TO-220AC | 1.3 | 23 | 0.9240 | 0.0476 | -0.002753 | -0.00001676 |
| 15 | VS-E5TX1506S2LHM3 | $D^2$PAK 2L (TO-263AB 2L) | 1.3 | 23 | 0.9240 | 0.0476 | -0.002753 | -0.00001676 |
| 15 | VS-E5TX1506THN3 | TO-220AC | 1.3 | 23 | 0.9240 | 0.0476 | -0.002753 | -0.00001676 |
| 30 | VS-A5PH3006LHN3 | TO-247AD 3L | 1.15 | 41 | 0.8470 | 0.0163 | -0.002239 | 0.00001735 |
| 30 | VS-A5PH3006L-N3 | TO-247AD 3L | 1.15 | 41 | 0.8470 | 0.0163 | -0.002239 | 0.00001735 |
| 30 | VS-A5PX3006LHN3 | TO-247AD 3L | 1.3 | 39 | 0.9181 | 0.0230 | -0.002739 | 0.0000004088 |
| 30 | VS-A5PX3006L-N3 | TO-247AD 3L | 1.3 | 39 | 0.9181 | 0.0230 | -0.002739 | 0.0000004088 |
| 30 | VS-E5PH3006LHN3 | TO-247AD 2L | 1.15 | 41 | 0.8470 | 0.0163 | -0.002239 | 0.00001735 |
| 30 | VS-E5PH3006L-N3 | TO-247AD 2L | 1.15 | 41 | 0.8470 | 0.0163 | -0.002239 | 0.00001735 |
| 30 | VS-E5PX3006LHN3 | TO-247AD 2L | 1.3 | 39 | 0.9181 | 0.0230 | -0.002739 | 0.0000004088 |
| 30 | VS-E5PX3006L-N3 | TO-247AD 2L | 1.3 | 39 | 0.9181 | 0.0230 | -0.002739 | 0.0000004088 |
| 30 | VS-E5TH3006-M3 | TO-220AC | 1.15 | 41 | 0.8429 | 0.0176 | -0.002247 | 0.0000142 |
| 30 | VS-E5TH3006S2LHM3 | $D^2$PAK 2L (TO-263AB 2L) | 1.15 | 41 | 0.8429 | 0.0176 | -0.002247 | 0.0000142 |
| 30 | VS-E5TH3006THN3 | TO-220AC | 1.15 | 41 | 0.8429 | 0.0176 | -0.002247 | 0.0000142 |
| 30 | VS-E5TX3006-M3 | TO-220AC | 1.3 | 39 | 0.9276 | 0.0242 | -0.002788 | -0.000005987 |
| 30 | VS-E5TX3006S2LHM3 | $D^2$PAK 2L (TO-263AB 2L) | 1.3 | 39 | 0.9276 | 0.0242 | -0.002788 | -0.000005987 |
| 30 | VS-E5TX3006THN3 | TO-220AC | 1.3 | 39 | 0.9276 | 0.0242 | -0.002788 | -0.000005987 |
| 60 | VS-A5PH6006LHN3 | TO-247AD 3L | 1.2 | 49 | 0.8538 | 0.0091 | -0.002201 | 0.00001101 |
| 60 | VS-A5PH6006L-N3 | TO-247AD 3L | 1.2 | 49 | 0.8538 | 0.0091 | -0.002201 | 0.00001101 |
| 60 | VS-A5PX6006LHN3 | TO-247AD 3L | 1.4 | 44 | 0.9443 | 0.0128 | -0.002838 | 0.000003013 |
| 60 | VS-A5PX6006L-N3 | TO-247AD 3L | 1.4 | 44 | 0.9443 | 0.0128 | -0.002838 | 0.000003013 |
| 60 | VS-E5PH6006LHN3 | TO-247AD 2L | 1.2 | 49 | 0.8538 | 0.0091 | -0.002201 | 0.00001101 |
| 60 | VS-E5PH6006L-N3 | TO-247AD 2L | 1.2 | 49 | 0.8538 | 0.0091 | -0.002201 | 0.00001101 |
| 60 | VS-E5PX6006LHN3 | TO-247AD 2L | 1.4 | 44 | 0.9443 | 0.0128 | -0.002838 | 0.000003013 |
| 60 | VS-E5PX6006L-N3 | TO-247AD 2L | 1.4 | 44 | 0.9443 | 0.0128 | -0.002838 | 0.000003013 |
| 75 | VS-E5PH7506LHN3 | TO-247AD 2L | 1.2 | 52 | 0.8210 | 0.0071 | -0.002134 | 0.000009555 |
| 75 | VS-E5PH7506L-N3 | TO-247AD 2L | 1.2 | 52 | 0.8210 | 0.0071 | -0.002134 | 0.000009555 |
| 75 | VS-E5PX7506LHN3 | TO-247AD 2L | 1.4 | 44 | 0.9004 | 0.0101 | -0.002707 | 0.000009592 |
| 75 | VS-E5PX7506L-N3 | TO-247AD 2L | 1.4 | 44 | 0.9004 | 0.0101 | -0.002707 | 0.000009592 |

**Note**

- Coefficient valid for current $I_F \leq 2$ times rated current

# How to Calculate Power Losses in Gen 5 Diodes

**TABLE 2**

| $I_{F(AV)}$ (A) | DEVICE | PACKAGE | $V_F$ at $I_F$ (V) | $t_{rr}$ (ns) | $V_{TO}$ (25 °C) (V) | $R_D$ (25 °C) (Ω) | $k_V$ (°C$^{-1}$) | $k_R$ (°C$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 8 | VS-E5TH0812-M3 | TO-220AC | 1.8 | 100 | 1.0776 | 0.1162 | -0.002702 | 0.000133 |
| 8 | VS-E5TH0812THN3 | TO-220AC | 1.8 | 100 | 1.0776 | 0.1162 | -0.002702 | 0.000133 |
| 8 | VS-E5TX0812-M3 | TO-220AC | 2.1 | 87 | 1.2269 | 0.1696 | -0.003774 | -0.00000323 |
| 8 | VS-E5TX0812THN3 | TO-220AC | 2.1 | 87 | 1.2269 | 0.1696 | -0.003774 | -0.00000323 |
| 15 | VS-E5TH1512-M3 | TO-220AC | 1.7 | 95 | 1.0609 | 0.0585 | -0.002664 | 0.00006709 |
| 15 | VS-E5TH1512S2LHM3 | D$^2$PAK 2L (TO-263AB 2L) | 1.7 | 95 | 1.0609 | 0.0585 | -0.002664 | 0.00006709 |
| 15 | VS-E5TH1512THN3 | TO-220AC | 1.7 | 95 | 1.0609 | 0.0585 | -0.002664 | 0.00006709 |
| 15 | VS-E5TX1512-M3 | TO-220AC | 2.1 | 96 | 1.2161 | 0.0823 | -0.003693 | 0.000008099 |
| 15 | VS-E5TX1512S2LHM3 | D$^2$PAK 2L (TO-263AB 2L) | 2.1 | 96 | 1.2161 | 0.0823 | -0.003693 | 0.000008099 |
| 15 | VS-E5TX1512THN3 | TO-220AC | 2.1 | 96 | 1.2161 | 0.0823 | -0.003693 | 0.000008099 |
| 30 | VS-E5PH3012LHN3 | TO-247AD 2L | 1.7 | 113 | 1.0841 | 0.0315 | -0.003002 | 0.00003497 |
| 30 | VS-E5PX3012LHN3 | TO-247AD 2L | 2.1 | 100 | 1.2325 | 0.0439 | -0.003883 | -0.000004865 |
| 30 | VS-E5TH3012-M3 | TO-220AC | 1.7 | 113 | 1.0841 | 0.0315 | -0.003002 | 0.00003497 |
| 30 | VS-E5TH3012S2LHM3 | D$^2$PAK 2L (TO-263AB 2L) | 1.7 | 113 | 1.0841 | 0.0315 | -0.003002 | 0.00003497 |
| 30 | VS-E5TH3012THN3 | TO-220AC | 1.7 | 113 | 1.0841 | 0.0315 | -0.003002 | 0.00003497 |
| 30 | VS-E5TX3012-M3 | TO-220AC | 2.1 | 100 | 1.2325 | 0.0439 | -0.003883 | -0.000004865 |
| 30 | VS-E5TX3012S2LHM3 | D$^2$PAK 2L (TO-263AB 2L) | 2.1 | 100 | 1.2325 | 0.0439 | -0.003883 | -0.000004865 |
| 30 | VS-E5TX3012THN3 | TO-220AC | 2.1 | 100 | 1.2325 | 0.0439 | -0.003883 | -0.000004865 |
| 60 | VS-E5PH6012LHN3 | TO-247AD 2L | 1.7 | 130 | 1.0506 | 0.0150 | -0.002767 | 0.00002112 |
| 60 | VS-E5PX6012LHN3 | TO-247AD 2L | 2.1 | 120 | 1.2296 | 0.0224 | -0.00394 | 0.000001132 |
| 30 | VS-E5PX3012L-N3 | TO-247AD | 2.1 | 26 | 1.2325 | 0.0439 | -0.003883 | -0.000004865 |
| 30 | VS-E5TX3012-N3 | TO-220AC | 2.1 | 26 | 1.2325 | 0.0439 | -0.003883 | -0.000004865 |
| 30 | VS-E5PH3012L-N3 | TO-247AD | 1.7 | 32 | 1.0841 | 0.0315 | -0.003002 | 0.00003497 |
| 30 | VS-E5TH3012-N3 | TO-220AC | 1.7 | 32 | 1.0841 | 0.0315 | -0.003002 | 0.00003497 |
| 60 | VS-E5PX6012L-N3 | TO-247AD | 2.1 | 30 | 1.2296 | 0.0224 | -0.00394 | 0.000001132 |
| 60 | VS-E5PH6012L-N3 | TO-247AD | 1.7 | 38 | 1.0506 | 0.0150 | -0.002767 | 0.00002112 |

**Note**

- Coefficient valid for current $I_F \leq 2$ times rated current

# How to Calculate Power Losses in Gen 5 Diodes

### BEHAVIOR OF REVERSE CURRENT

During the OFF state, the diode can't be polarized or the voltage anode cathode is negative.

The leakage current is a function of the reverse voltage and temperature. The leakage current for 30 A, 600 V, and 1200 V devices is plotted in Fig. 12 and Fig. 13.

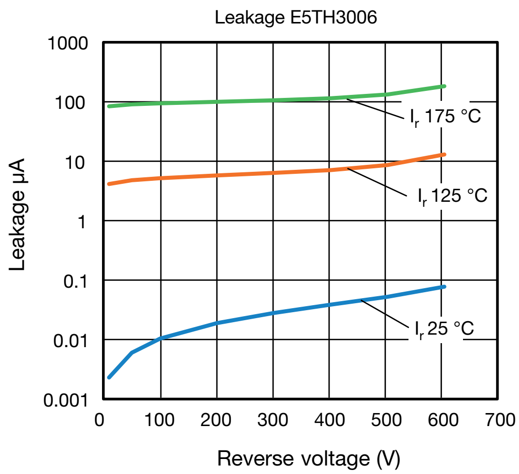



Fig. 12 - VS-E5TH3006 Leakage Current as a Function of Cathode Anode Voltage and Temperature

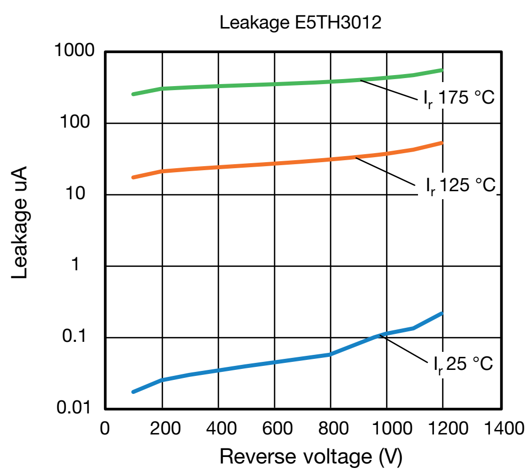



Fig. 13 - VS-E5TH3012 Leakage Current as a Function of Cathode Anode Voltage and Temperature

The temperature is a key parameter for the leakage because its behavior is exponential with temperature.

The absolute value is very small, but at a high voltage - for example, 1000 V - 1 mA gives a dissipated power of 1 W. The leakage current grows with temperature, as in Formula 1.8.

**1.8** $I_R = I_{R0}(V_R) \times \exp(C(V_R) \times T_j)$

Usually, if the working $T_j$ is lower than 150 °C, its contribution is negligible and the evaluation of losses could be left out, particularly for 600 V devices. In Fig. 14, the behavior of the VS-E5PH3006 as a function of temperature is plotted.

# How to Calculate Power Losses in Gen 5 Diodes

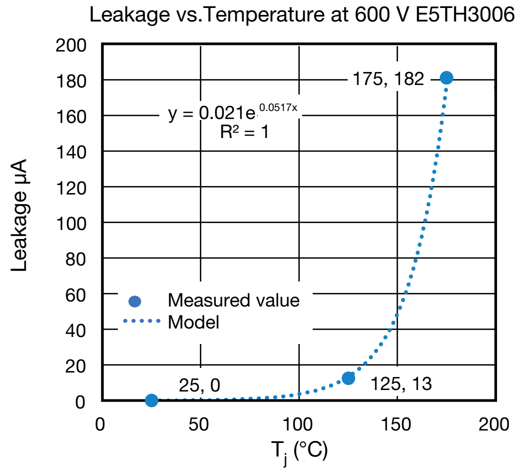



Fig. 14 - VS-E5TH3012 Leakage Current as a Function of Temperature, with a Cathode Anode Voltage of 600 V

For Gen 5 600 V, 30 A diodes, if the reverse voltage is 600 V and $T_j$ is 175 °C, the leakage current typically is 182 µA, which means that dissipated power is 600 V x 182 µA = 109 mW. Also, for a device without a heatsink, the level of dissipated power is negligible. In the datasheet there is also a maximum value at $T_j$ = 125 °C given that is not a limit of the device; it is a value obtained from statistical analysis of data that indicates the threshold where the probability of finding a device with this value of leakage current is near to zero. If this value is used for a worst case analysis, it gives a very large margin that isn't realistic. For an evaluation of the leakage current contribution, it's better to refer to the datasheet's graph of "Typical Values of Reverse Current vs. Reverse Voltage".

For a 1200 V device, the leakage current is a little bit higher. The real difference in reverse losses, however, is the level of voltage, which for 1200 V applications is usually nearly double compared with circuits using 600 V devices.

As an example, the VS-E5TX3012 has at 1000 V (a high voltage, but possible in many applications) and a $T_j$ of 175 °C a typical leakage of around 530 µA. The dissipated power is 1000 V x 530 µA = 530 mW, which in a marginal device could be little bit higher. 0.6 W of losses in reverse polarization is a worst case scenario with a small probability, but is still possible. The reverse polarization losses should be multiplied for the time that the device is in the OFF condition with applied reverse voltage. Usually, for a device on a heatsink, the power due to reverse losses is negligible for 600 V devices. For 1200 V devices, if the reverse voltage is over 800 V, it's best to do a quick check to verify that reverse polarization power losses are negligible, especially if the device works without a heatsink.

The leakage at certain temperatures could be evaluated from the datasheet using Formula 1.8, keeping in mind that values obtained from the maximum are only statistical limits, and their use in real evaluations give an overestimation of real losses.

$I_{R0}$ and C could be evaluated from the datasheet, and are valid for a fixed reverse voltage.

For Gen 5 diodes, $I_{R0}$ and C are quite constant if the reverse voltage doesn't change too much, so it's not necessary to re-evaluate the coefficient if the reverse voltage does not change more than ± 100 V.

# How to Calculate Power Losses in Gen 5 Diodes

## EXAMPLE OF EVALUATION

Let's consider an LLC rectifier for a 22 kW on-board charger (OBC, Fig. 15) that is working at near to resonance at 100 kHz, with 700 V of output voltage and 32 A of output current.
The system is air-cooled.

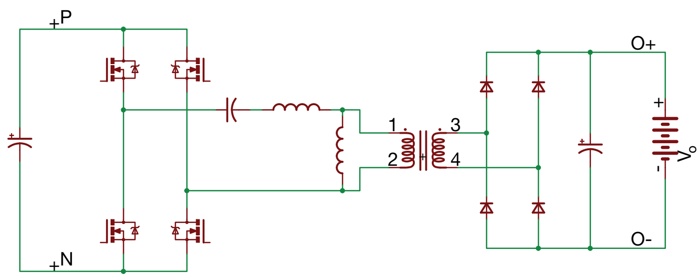



Fig. 15 - LLC Converter

The current at the output of the rectifier has the following shape:

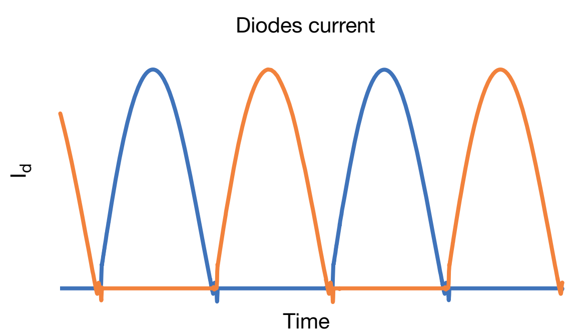



Fig. 16 - Simplified Current Waveform at the Rectifier Output

The current could be considered sinusoidal and the duty cycle for each diode branch is around 46 % of the total switching period.

Considering a full-bridge rectifier, the average current for each diode is half of the total output current, so 16 A.

From the table in Figure A, the sinusoidal current and peak current in the diode is:

**1.9** $$I_{max.} = \left(\frac{I_{Favd} \times \pi}{2}\right)/d = \left(\frac{16 \times \pi}{2}\right)/0.42 = 59.83 \text{ A}$$

So, the RMS current through each diode is:

**2.0** $$I_{RMS} = I_{max} \times \sqrt{\left(\frac{0.42}{2}\right)} = 59.83 \times \sqrt{0.21} = 27.41 \text{ A}$$

With a peak current of 59.8 A, average of 16 A, and reverse voltage of 700 V, the first choice could be the VS-E5TH3012.

The H speed is preferred because with an LLC circuit, switching losses are kept low by the natural behavior of the current, and a high current suggests a device with low forward voltage.

The power dissipated in each diode can be calculated with Formula 1.6 and the values in Table 2. Generally, in a steady-state condition the $T_j$ will not be 25 °C if system is not liquid cooled, so an initial $T_j$ could be 75 °C. With Formula 1.7 it is possible to evaluate the $V_{to}$ $R_d$ at 75 °C:

# How to Calculate Power Losses in Gen 5 Diodes

**2.1**

$$V_{T0}(T_j) = k_V \times (T_j - 25) + V_{T0}\ (25\ °C) = -3.002E - 3\frac{V}{°C} \times (75\ °C - 25\ °C) + 1.084V = 0.934V$$

$$R_D(T_j) = k_R \times (T_j - 25) + R_D\ (25\ °C) = -3.497E - 5\frac{V}{°C} \times (75\ °C - 25\ °C) + 0.0315\ \Omega = 0.0332\ \Omega$$

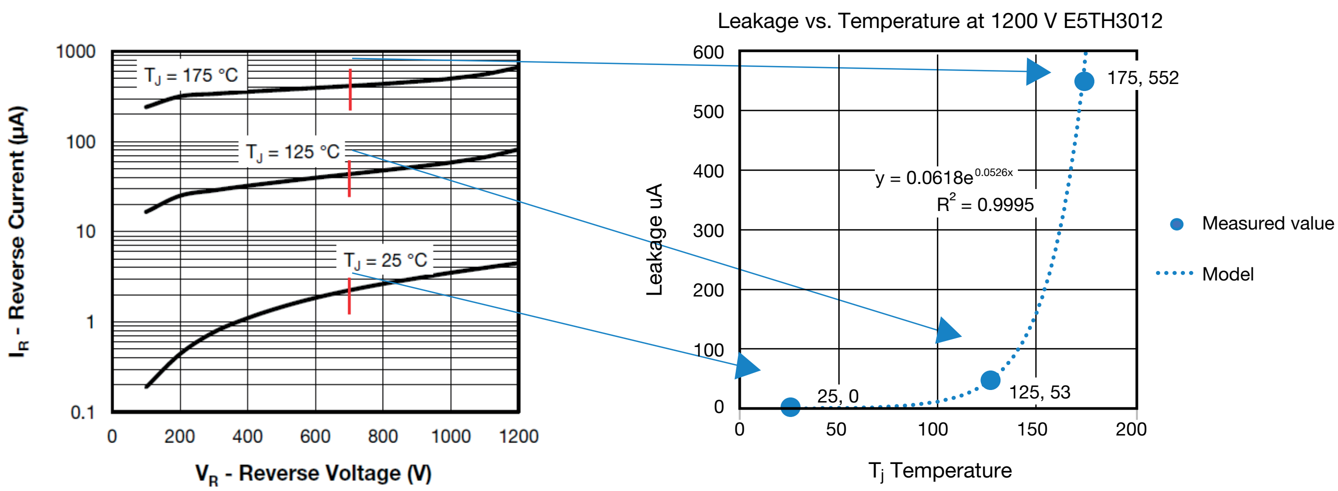
The dissipated power from formula 1.6:

**2.2**

$$P_D = V_{T0} \times Id_{AVG} + R_D \times Id^2{}_{RMS} = 0.934\ V \times 16\ A + 0.0332\ \Omega \times (27.41\ A)^2 = 39.89\ W$$

This is the power dissipated in the device during the ON phase; for the 52 % of cycle time the device is in reverse with a reverse voltage $V_{OUT}$ + 2 $V_F$ to simplify $V_{OUT}$, which is 700 V.

The leakage at 75 °C could be evaluated from the datasheet - From Typical Values of Reverse Current vs. Reverse Voltage and formula 1.8.




Formula 1.8 became $I_R$ = 0.0618 x exp (0.0526 x $T_j$) = 0.0618 x exp x (0.0526 x 75) = 3.2 µA at 700 V, which means 2.3 mW is negligible at a temperature around 75 °C. The dissipated power for static losses is 39.9 W. In this condition, LLC under frequency resonance, these are the total losses, because switching losses are negligible.

Considering the worst case $R_{th}$ from the datasheet of 1.2° C/W, and a heatsink thermal resistance of 1.5 °C/W at 40 °C of ambient, the $T_j$ is determined by formula 2.3.

**2.3**

$$T_j = (R_{thjc} + R_{thca}) \times P_D + T_{amb} = \left(1.2\frac{°C}{W} + 1.5\ \frac{°C}{W}\right) \times 39.9\ W + 40\ °C = 147\ °C$$

This temperature is far from 75 °C, so it is better to redo the evaluation considering $T_j$ = 147 °C. Back with formula 2.1, the evaluation becomes:

**2.4**

$$V_{T0}(T_j) = k_V \times (T_j - 25) + V_{T0}\ (25\ °C) = -3.002E - 3\frac{V}{°C} \times (147\ °C - 25\ °C) + 1.084\ V = 0.718V$$

$$R_D(T_j) = k_R \times (T_j - 25) + R_D\ (25\ °C) = -3.497E - 5\frac{V}{°C} \times (147\ °C - 25\ °C) + 0.0315\ \Omega = 0.0358\ \Omega$$

The dissipated power from formula 1.6:

**2.5** $$P_d = V_{T0} \times Id_{AVG} + R_D \times Id^2{}_{RMS} = 0.718\ V \times 16\ A + 0.0358\ \Omega \times (27.41\ A)^2 = 38.38\ W$$

# How to Calculate Power Losses in Gen 5 Diodes

Formula 1.8 becomes $I_R$ = 0.0618 x exp (0.0526 x $T_j$) = 0.0618 x exp x (0.0526 x 147 °C) = 141 μA at 700 V, which means that 98.7 mW is much higher than the previous evaluation, but as an absolute value is negligible compared to 38.38 W.

The $T_j$ evaluation becomes:

**2.6** $$T_j = (R_{thjc} + R_{thca}) \times P_D + T_{amb} = \left(1.2\frac{°C}{W} + 1.5\ \frac{°C}{W}\right) \times 38.38\ W + 40\ °C = 143\ °C$$

Now the evaluated $T_j$ is near the previous value, so this could be considered correct. The $T_j$ is considered correct when the difference between the two steps is less than 5 °C.

The analysis of more complex circuits is possible, and simplified it is enough to evaluate the average and RMS current in the diode. For example, in a T-type Vienna rectifier (Fig. 17), the diode works as a boost device, switching at certain frequencies (such as 10 kHz - 20 kHz) for a half period and for the other half period it is in reverse.

$$M = \frac{V_{inpk}}{\frac{1}{2}V_{PN}}$$

$$I_{Davg} = I_0\frac{M}{4}$$

$$I_{DRMS} = I_0\sqrt{\frac{2M}{3\pi}}$$

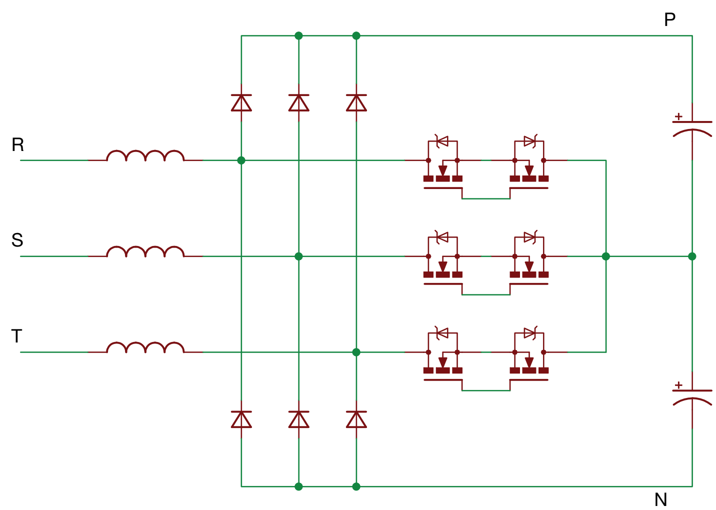



Fig. 17 - T-type Vienna Rectifier

The input voltage is 400 $V_{AC}$ and power is 22 kW, with a DC bus of 750 V and switching frequency of 20 kHz. From these data, the average current in the diodes is 9.78 A for each. The modulation factor M is

**2.7** $$M = \frac{V_{inpk}}{\frac{1}{2}V_{PN}}$$

With 400 $V_{AC}$, $V_u$ is 565.7 V, so M = 565.7 V / (1/2 x 750 V) = 1.508. From the average current, it is possible to calculate the peak current $I_A = I_{Davg}$ x 4/M = 9.78 A x 4/1.508 = 25.94 A

From Figure A, it is possible obtain

$$I_{DRMS} = Ia \times \sqrt{\left(\frac{2 \text{ x } M}{3 \text{ x } \pi}\right)} = 25.94 \times \sqrt{\left(2 \times \frac{1.508}{3 \text{ x } \pi}\right)} = 12.45\ A$$

For the T-type Vienna circuit, switching losses are not negligible, so usually a diode larger than 1.5 times the peak current is the starting point. The switching frequency is 20 kHz, so it is possible to do a preliminary evaluation with device X speed thinking di/dt higher than 500 A/μs. A suitable device could be the VS-E5PX6012L in the hypothesis of an initial $T_j$ around 75 °C using Formula 1.7

# How to Calculate Power Losses in Gen 5 Diodes

**2.8**

$$V_{T0}(T_j) = k_V \times (T_j - 25) + V_{T0}\ (25\ °C) = -3.940E - 3\frac{V}{°C} \times (75\ °C - 25\ °C) + 1.2296\ V = 1.032\ V$$

$$R_D(T_j) = k_R \times (T_j - 25) + R_D\ (25\ °C) = -1.1323E - 6\frac{V}{°C} \times (75\ °C - 25\ °C) + 0.0224\ \Omega = 0.02246\ \Omega$$

The dissipated power could be evaluate from Formula 1.6 using above $V_{to}$ $R_d$

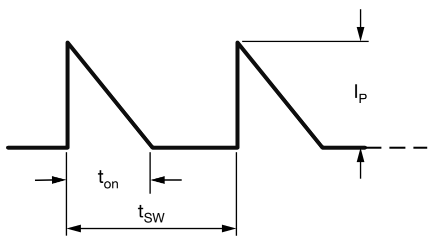
**2.9**

$$P_D = V_{T0} \times Id_{AVG} + R_D \times Id^2{}_{RMS} = 1.032\ V \times 9.78\ A + 0.02246\ \Omega \times (12.45\ A)^2 = 13.57\ W$$

For the T-type Vienna circuit, the switching losses are not negligible and should be added at the conduction losses for the evaluation of $T_j$. The reverse losses at 750 V are hundreds of µA and associated losses evaluated on the half cycle at 750 V are only 100 µA (worst case), and with a duty cycle of 50 % give 37.5 mW of losses. The value should be updated with temperature, but at 75 °C the contribution is negligible. After the evaluation of $T_j$ is done with all the losses, it's possible to update formula 2.8 and start the iterative process. In circuits like power factor correction (PFC) or motor drives where the envelope of modulation is sinusoidal, 10 ms or similar, it's important at the end of the process to do a verification of the peak temperature of the diode during the cycle. The average temperature is correct, but the peak of $T_j$ could be higher, so a quick check on $T_j$ peak, which should be lower than 175 °C, is recommended.

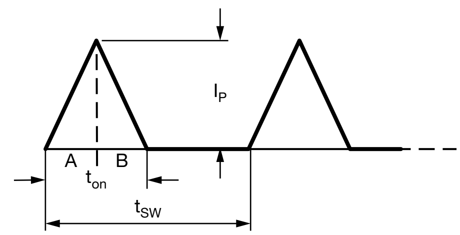
# How to Calculate Power Losses in Gen 5 Diodes

**Figure A**



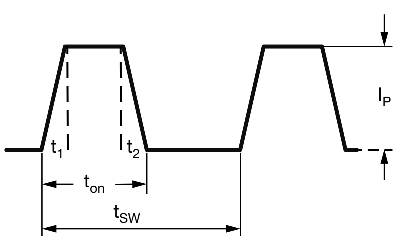

$$I_{AV} = \frac{I_P\, t_{on}}{2\, t_{SW}}$$

$$I_{RMS}{}^2 = \frac{I_P{}^2\, t_{on}}{3\, t_{SW}}$$



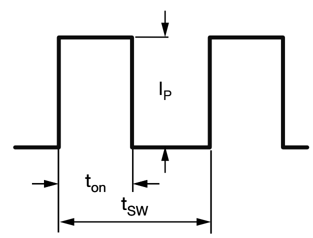

$$I_{AV} = \frac{I_P}{t_{SW}} \left(\frac{A}{2} + \frac{B}{2}\right)$$

$$I_{RMS}{}^2 = \frac{I_P{}^2\, (A + B)}{3\, t_{SW}}$$



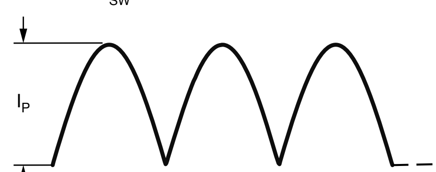

$$I_{AV} = \frac{I_P}{2\, t_{SW}} \times (2\, t_{on} - t_1 - t_2)$$

$$I_{RMS}{}^2 = \frac{I_P{}^2}{3\, t_{SW}} \times (3\, t_{on} - 2\, t_1 - 2\, t_2)$$



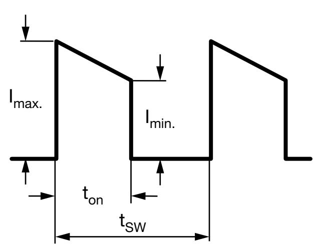

$$I_{AV} = \frac{I_P\, t_{on}}{t_{SW}}$$

$$I_{RMS}{}^2 = \frac{I_P{}^2\, t_{on}}{t_{SW}}$$



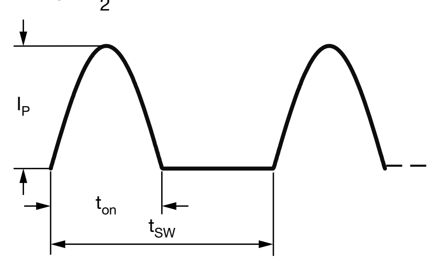

$$I_{AV} = \frac{2\, I_P}{\pi}$$

$$I_{RMS}{}^2 = \frac{I_P{}^2}{2}$$




$$I_{AV} = \frac{(I_{max.} + I_{min.})\, t_{on}}{2\, t_{SW}}$$

$$I_{RMS}{}^2 = \frac{(I_{max.}{}^2 + I_{min.}{}^2 + I_{max.}\, I_{min.})\, t_{on}}{3\, t_{SW}}$$

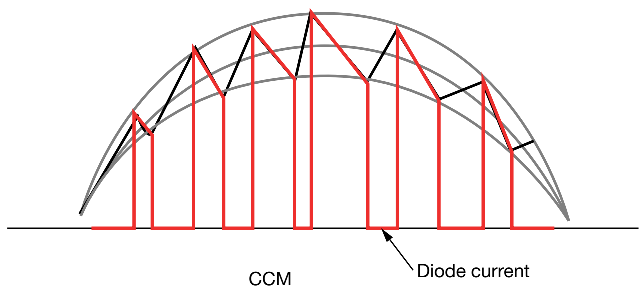


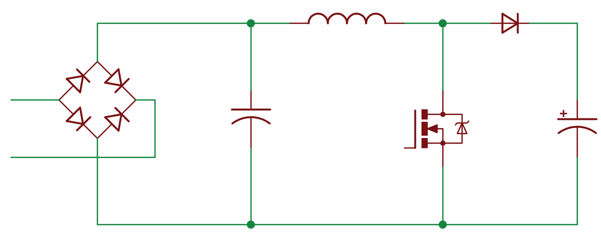

$$I_{AV} = \frac{2\, I_P\, t_{on}}{\pi\, t_{SW}}$$

$$I_{RMS}{}^2 = \frac{I_P{}^2\, t_{on}}{2\, t_{SW}}$$

# How to Calculate Power Losses in Gen 5 Diodes

**Figure A**



$$I_{AV} = \frac{P_0}{V_0}$$

$$I_{RMS} = \frac{P_0}{V_0}\sqrt{\frac{16\ V_0}{3\ \pi\ V_{IN}\sqrt{2}}}$$

$$M = \frac{V_{inpk}}{1/2\ V_{PN}}$$

$$I_{Davg} = I_a\frac{M}{2}$$

$$I_{DRMS} = I_a\sqrt{\frac{2\ M}{3\ \pi}}$$