

## X-Series RFC Diodes for Robust and Reliable Medium-Voltage Drives

*The three-level neutral-point-clamped converter is popular and often used in medium-voltage drives for instance. This article explains the popularity of the topology, the semiconductor requirements, and how the new X-Series diode module of MITSUBISHI ELECTRIC can make this converter more robust and more reliable.*

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### Three-Level Neutral-Point-Clamped Converter

The three-level neutral-point-clamped converter (NPC) is a typical converter topology for high-power medium-voltage applications. The NPC converter is used in various applications: in offshore-wind generators, STATCOMs, rolling mills, conveyor starters or even ship propulsion systems. What is special about this topology?

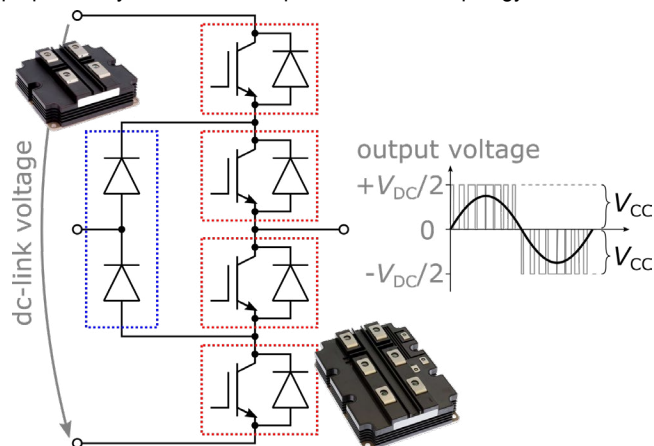


Figure 1: Three-Level Neutral-Point-Clamped (NPC) Converter made of IGBT modules (red) and diode modules (blue)

Figure 1 shows the principle schematic of an NPC converter. It consists of four main IGBTs which are marked in the figure by the red boxes. For one inverter arm, two IGBTs are connected in series. This gives the first advantage of the NPC converter: its dc-link voltage V<sub>DC</sub> can be twice as high compared to a two-level converter.

Furthermore, the NPC converter utilizes clamping diodes (marked by a blue box). Due to these diodes, the NPC converter is able to output three different voltage levels ( $+\frac{V_{DC}}{2}$ , 0,  $-\frac{V_{DC}}{2}$ ). The additional output level allows a lower total harmonic distortion (THD) compared to a two level converter. This results in smaller and more efficient output filters.

As shown in Figure 1, the output voltage makes steps of  $\frac{V_{DC}}{2}$ . This gives two advantages. Firstly, the switching losses of the semiconductors are lower, due to the lower switching voltage V<sub>CC</sub>. Secondly, common-mode currents are reduced. These current might cause electromagnetic interference (EMI) and damage of bearing and motors.

In summary, a three-level NPC converter offers the following advantages over a two-level converter:

- Higher achievable dc-link and output voltage
- Smaller, more efficient output filter
- Higher switching frequencies
- Lower common-mode currents

### Application Field

The NPC converter is today used in various applications. Looking at three exemplary applications, we will see quite different technical converter requirements.

The first example is a grid-side converter of an offshore wind turbine injecting power from the wind generator into the grid. Therefore, the grid-side converter mainly operates at a power factor cos( $\varphi$ ) close to 1. It is operated directly at the grid or via a filter. Hence, only small variation of the modulation index  $m$  are required.

As a second example, the generator-side converter of an offshore wind turbine is regarded. Since power flow is from AC- to DC-side, it is operated with negative power factor. Moreover, the converter's modulation index is varying according to the speed of the wind generator and the generator voltage.

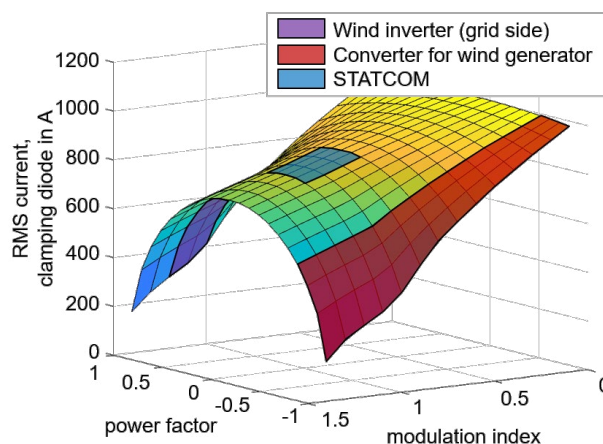


Figure 2: RMS current in the clamping diode for different converter operation conditions

The last example is a STATCOM converter to supply reactive power to a grid. It might be operating at a power factor around 0 depending on the reactive power demand by the grid. Assuming a constant grid voltage, again the maximal modulation index is relatively constant.

The impact on the diode module of the three-level NPC converter (cf. Figure 1 blue box) for each application shall be analyzed. For this, an NPC converter with a constant dc-link voltage of 5000 V, a sinusoidal output current of 1500 A (RMS), switching frequency of 600 Hz and output frequency of 50 Hz is considered.

Figure 2 shows the RMS current in the upper clamping diode as an indicator for the losses and the thermal stress of the diode module. It can be seen, that while the converter's output current is 1500 A, the current through the clamping diode is lower. Secondly, it can be seen that the highest current occurs for low modulation indices. Finally, the figure reveals that the highest current occurs for a power factor around 0.

According to Figure 2, the current rating of the clamping diodes in a three-level NPC converter is highly dependent on the application. If chosen wrongly, the converter won't be competitive in terms of performance or price. For every customer and every application, the optimal diode module has to be found therefore.

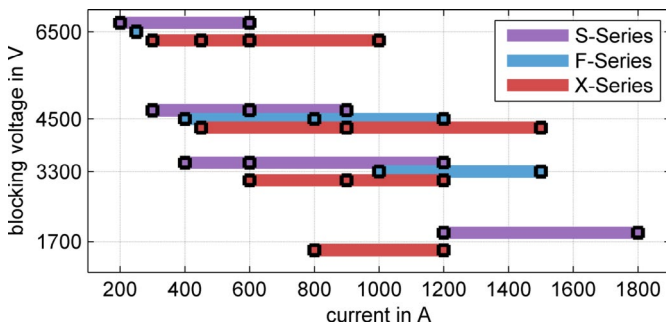


Figure 3: Mitsubishi Electric high-voltage diode-module lineup

Due to this reason, Mitsubishi Electric offers a wide portfolio of IGBT as well as diode modules. An overview of the diode module line-up is given in Figure 3. High-voltage diode modules are available from 1.7 kV to 6.5 kV blocking voltage. Moreover, diode generations range from S- and F-Series to X-Series, the newest development. The X-Series diode modules utilize the same RFC diodes like the X-Series IGBT modules. However, also the combination of X-Series IGBT together with a S- or F-Series diode module as clamping diode can be considered. An exemplary measurement is shown in Figure 4.

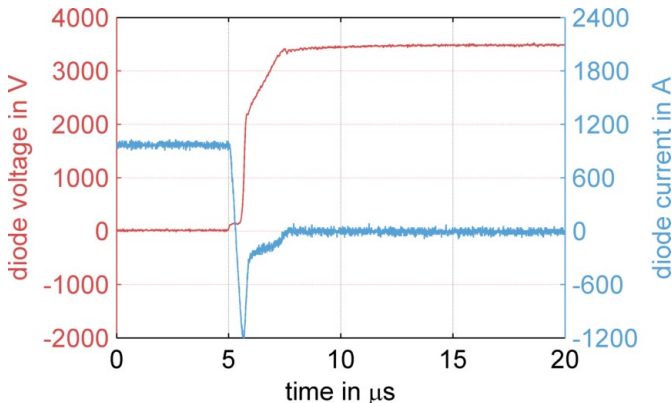


Figure 4: Reverse recovery waveform of S-Series diode module switched with X-Series IGBT (RM600DG-130S, CM900HG-130X, Conditions:  $T_j = 25^\circ\text{C}$ ,  $V_{cc} = 3500\text{ V}$ ,  $I_c = 1000\text{ A}$ ,  $L_s = 150\text{ nH}$ )

### X-Series RFC Diode

MITSUBISHI ELECTRIC now launches the new diode modules which use the same RFC diode chips, like in the X-Series IGBT modules. Already in the IGBT modules, these diode chips have proven their

- High robustness and large safe operating area,
- Smooth switching even at high stray inductance,
- High surge current and  $I^2t$  capability,
- High current ratings,
- Low power loss, and
- $150^\circ\text{C}$  maximum junction temperature for all voltage classes.

These advantages are now transferred to dual-diode modules in the well know 130x140 mm package. Figure 5 shows the 6.5kV diode-module package as an example.

The RFC diode, which stands for Relaxed-Field at Cathode, has a special P and N+ doping pattern at the backside of the chip as illustrated in Figure 6. This backside pattern allows smooth switching transients (for low EMI) and strong robustness. This RFC diode has been proposed originally in [1]. Since then, it has been improved continuously [2] [3] [4] [5] [6].

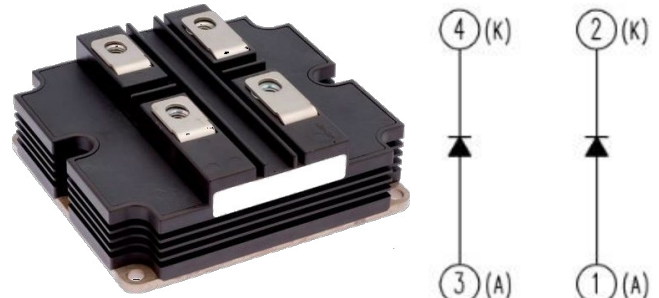


Figure 5: Outline and circuit diagram of a 6.5kV / 1000A diode module (type name: RM1000DG-130XA)

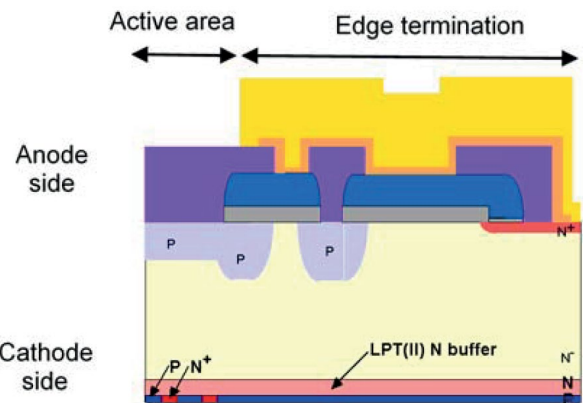


Figure 6: Chip structure of the RFC diode

Figure 7 shows the forward voltage drop of two different 6.5 kV diode modules both in the same package outline. Violet curve shows a 600 A module from a previous generation, red curve shows the 1000 A X-Series diode module. Hence, the conduction losses have been reduced substantially. This allows for higher output power, higher efficiency and more compact converters.

Also the robustness of the diode was increased significantly. A typical measure for diode robustness is surge current or  $I^2t$  capability. For it, the diode has to withstand a half-sine wave current pulse whose peak value is usually substantially higher than the nominal current rating. The peak value of the surge current or the integral of the current-

squared is usually indicated in the datasheet. A larger surge current capability is desired for example in case of a short circuit at in the converter.

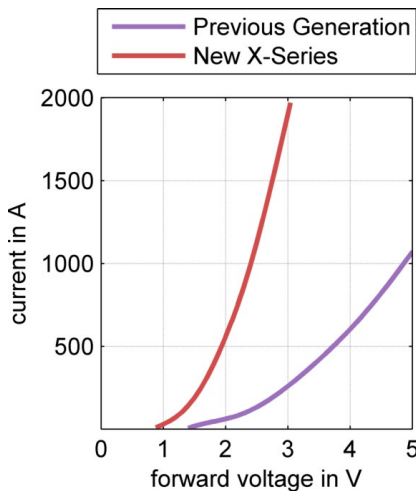


Figure 7: Comparison of 6.5 kV X-Series diode module (RM1000DG-130XA) and previous generation in forward voltage drop for  $T_j=25^\circ\text{C}$

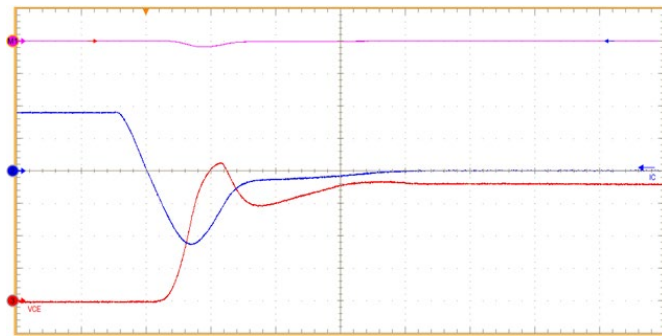


Figure 8: 3.3 kV X-Series diode switches off at high dc-link inductance ( $I_c = 1800\text{A}$ ,  $V_{cc} = 1800\text{V}$ ,  $T_j = 25^\circ\text{C}$ ,  $L_s = 300\text{ nH}$ ) [ $1\text{ }\mu\text{s/div}$ ,  $500\text{ V/div}$  (red),  $1000\text{ A/div}$  (blue)]

Comparing the surge current capability of the new 4.5 kV X-Series RFC diode with an older generation shows the big improvement. Consequently, surge current capability and  $I^2t$  capability are increased by 38 % and 129 % respectively.

Especially in multi-level converters, the parasitic inductance  $L_s$  of the dc-link might increase substantially due to more complex busbars and larger commutation loops. Figure 8 shows the switching waveform of a 3.3 kV X-Series diode at large dc-link inductance of 300 nH. Even at these extreme conditions, the X-Series diode shows an expected and smooth switching behavior. This allows robust converter operation and a fast design-in process.

## Conclusion

Complementary to the well-accepted S- and F-Series diode modules, MITSUBISHI ELECTRIC just launched the new X-Series diode modules. From a large line-up, the optimal diode for applications like multi-level converter or dc choppers can be chosen. The X-Series diode modules use the latest development of the RFC diode. This increases the maximum current capability but also enhances the robustness of the diode. This is manifested by the increased surge current and  $I^2t$  capability. This, and the well-tempered switching behavior, allow reliable and robust medium-voltage converters.

	Previous Generation	New X-Series	Improvement
<b>Ratings</b>	4500V, 900A	4500V, 900A	
<b>Conditions</b>	$T_{j,\text{start}} = 25^\circ\text{C}$ , 60 Hz half-sine wave	$T_{j,\text{start}} = 150^\circ\text{C}$ , 50 Hz half-sine wave	
<b>Surge Current</b>	6400 A	8800 A	+ 38 %
<b><math>I^2t</math></b>	170 $\text{kA}^2\text{s}$	390 $\text{kA}^2\text{s}$	+ 129 %

Table 1: Diode robustness of new X-Series compared to a previous generation

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