SSFC rectifier power stages

A brief summary of the advantages and disadvantages of using IGBT’s and SCR’s in rectifier power stages

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1 Introduction

Based on their design principles, solid state frequency converters are equipped with input rectifiers. Since rectifiers cannot take in sinusoidal currents, they will distort the mains input current. The negative impacts of non-linear loads on the quality of the electrical energy supply are called system perturbations or more generally electrical pollution. This includes harmonics, flicker, transient faults, asymmetric and voltage outages. For units that are equipped with controlled or uncontrolled rectifiers and capacitors in the DC-Link, the input current waveform is far from sinusoidal. Besides solid state frequency converters there are many devices in the industry which are also equipped with input rectifiers. This increases the non-linear current in the network. Any device that draws a pulse of current from the electrical network for less than the entire voltage wave generates harmonics. Harmonics are simply a mathematical representation of these distorted waveforms that allow us to model electrical network response at multiple frequencies, and better understand and predict how the electrical network will react to this high-frequency content – or 'electrical pollution':

\[ i(t) = i_0^\ast + i_1^\ast \cdot \cos(\omega \cdot t + \varphi_1) + i_2^\ast \cdot \cos(2 \cdot \omega \cdot t + \varphi_2) + \ldots + i_n^\ast \cdot \cos(n \cdot \omega \cdot t + \varphi_n). \]

\( i_0 \) represents the dc content (zero in this case) and \( i_1 \) as the fundamental wave, while \( n = 2 \) to 40 represent the current harmonics (sometimes instead of \( n \), \( h \) or \( \upsilon \) are also used).

The European standards EN 61000-3-2 and EN 61000-3-12 specify harmonic content limits and require manufacturers to limit the harmonic content that their units can induce into the utility power. Finally, the world wide standard IEEE 519-1992 requires that end users limit harmonic levels to ensure network stability for all users. It outlines acceptable levels of harmonic distortion (both voltage and current) and the Point of Common Coupling (PCC) with the utility. What is the correct approach to limit or minimize the harmonic content at the converters input current? Different possibilities are available. Manufacturers can reduce harmonics by either using a phase shifting and multi-pulse rectifier transformer or an active front-end rectifier.
Traditionally, Solid State Frequency Converters (SSFC) have used Silicon Controlled Rectifiers (SCR) to convert AC power to DC power. SCR’s have the advantage of being easy to control and inexpensive. They just have to be turned on or off at the zero-crossing point of the AC sine wave. Unfortunately, they have several significant disadvantages. They create high harmonic distortions in the input current waveform. They lower the input power factor taking more reactive current and they induce commutation spikes into the utility power supply.

Isolated Gate Bipolar Transistors (IGBT) have several advantages over SCR’s. They do not have to be turned on and off at the zero crossing point, they do not change the input power factor or induce commutation spikes into the input power source. They also allow better control of the entire power and frequency conversion process. For these reasons, IGBT’s are now being used in high end SSFC’s just as they are used in state of the art solid state Uninterruptible Power Supplies (UPS).

Figure 1: Basic function of IGBT’s
2 Basic operation of SSFC’s rectifiers

To better understand the above points, let’s look at how each of these devices is used in the typical SSFC. A low end SSFC will have a pair of SCR’s for each phase of the power source. One SCR is turned on for the positive portion of the AC waveform and turned off at the next zero crossing. While the opposing SCR of the pair is turned on for the negative portion of the AC waveform and off at the next zero crossing. This on/off pattern is used to transmit full power to the output load.

A 12-pulse SCR system follows the same basic pattern but it splits the utility power into two 6-pulse rectifiers. The second 6-pulse rectifier is typically fed through a 30 degree phase shifting transformer. This provides a smoother DC current which puts less stress on the DC capacitors and shifts the input current harmonic distortion to higher frequencies with less energy content, but the design requires more components.

For both rectifier types (including versions with diodes instead of SCR’s) the energy will follow one direction only, which means the energy is only fed in the direction of the load. There is no way back.

Figure 2: 6pulse rectifier
IGBT's are also used in pairs for each phase of the power source.

Figure 3: 12pulse rectifier

Figure 4: IGBT rectifier

Figure 5: Pulse Width Modulation (PWM) principle
Instead of turning on and off at the zero crossing point IGBT's are fully controlled using Pulse Width Modulation (PWM) control algorithm.

PWM systems typically operate at much higher switching frequencies (6 – 8 kHz instead of 120 Hz for SCR's). The higher switching frequency allows much finer control of the power conversion process. It also does not produce the audible noise that is often found in low end systems. The width of each pulse determines the amount of power that is converted to DC in the rectifier. But, because there are thousands of pulses in each cycle the energy being transferred per pulse is small which gives the IGBT system significant advantages over an SCR system.

Since the transistor can conduct the current in both directions, it is possible to feed some power back to the utility in case the load creates some reverse power. This is another significant advantage over an SCR system (simple no break power transfer capability).

3 Harmonic Content

Whenever loads draw current in a non-linear manner, such as that experienced with rectifier based equipment, harmonic distortion is experienced. Harmonic current generates heat in all of the current carrying components of the electrical distribution system. The system includes not only the converters but also the upstream switchgear, breakers, fuses, cabling, capacitors, bus ducts, bus bars and transformers. Based on the higher frequency, harmonic current generates more heat on a per-Amp basis than current at the fundamental frequency (50 or 60 Hz).

Harmonic current flowing through the system impedances generates harmonic voltage distortion because of the voltage drop. The closer you get to the non-linear loads, the more distorted the voltage waveform becomes from a true sinusoid. In severe instances, voltage distortion can cause operational problems with sensitive electronic equipment such as programmable logic controllers (PLC’s) and drives. So, users at the end of the utility distribution in remote locations or users who operate under generator power are more likely to experience issues relating to excessive voltage distortion. With increased voltage distortion even linear loads will start to draw harmonic current.
The current requirements for the equipment range from tens of amps to several hundred amps. The percent of distortion is thus very large at low current levels and improves as the amount of current rises.

This is why some manufacturers will quote low THD numbers without indicating that it is for voltage, or will only give Total Harmonic current Distortion (THID) numbers at full load. (Properly written specifications which require THID values at 25%, 50%, 75% and 100% will ensure that you are comparing apples to apples in this area).

Typical levels of THID for six pulse rectifiers are listed in Figure 1-6. The % THID is representative of systems which do not have any means of filtering included in their input circuit. Filtering will lower these values at the expense of overall system efficiencies.

<table>
<thead>
<tr>
<th>KW</th>
<th>% THID</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 15 KW</td>
<td>&gt; 100 %</td>
</tr>
<tr>
<td>18 - 30 KW</td>
<td>80 - 100 %</td>
</tr>
<tr>
<td>37 - 112 KW</td>
<td>60 - 80 %</td>
</tr>
<tr>
<td>&gt; 150 KW</td>
<td>50 - 70 %</td>
</tr>
</tbody>
</table>

These THID values are high at lower loads, because the SCR’s are turned on later in the waveform. The later in the waveform the SCR is turned on, the greater the harmonic distortion that is reflected back into the utility grid.

The problem with high harmonic distortion is that it causes a decrease in overall system efficiency and shortens the lifespan of capacitors, transformers and semiconductors. High harmonic distortion results in higher power losses in upstream transformers and cable runs. This means that the utility has to provide more power to a unit using SCR’s than to the same size unit using IGBT’s which have lower levels of THID at each load point.
The harmonic content of 6-pulse rectifiers is strongest at the 5th & 7th harmonics thus current harmonics very strongly affect capacitors (i.e. pf compensation for the utility power). Also, upstream transformers isolate voltage but not current, thus current frequencies and distortions are passed through to all devices in the system. 12 pulse rectifiers have less of an effect on capacitors since their primary harmonics are at the 11th & 13th harmonics).

The IGBT design produces much lower harmonic distortion (<5%) compared to the SCR design on both the input and output waveforms. Therefore, whenever efficiencies and unit losses are measured, the total system losses should be measured at each load point. This will provide a better measurement of the energy requirements for the system and not just the individual piece of equipment, especially when that piece of equipment generates large losses in the upstream cables and transformers of the system.

The three graphs below are taken from a 6 pulse rectifier, 12 pulse rectifier and IGBT rectifier at full load (Figure 8 to 10). In each graph, the top waveform is the utility voltage and the bottom waveform is the input current of the SSFC.

Figure 8: 6 Pulse Rectifier Utility Power
Figure 9: 12 Pulse Rectifier Utility Power

Figure 10: IGBT Rectifier Utility Power
4 Input power factor

A power factor of one or "unity power factor" is the goal of any electric utility company since if the power factor is less than one, they have to supply more current to the user for a given amount of power use. In so doing, they incur more line losses. They also must have larger capacity equipment in place than would otherwise be necessary. As a result, a facility will be charged a penalty if its power factor is much different from one.

Most commercial facilities tend to have a "lagging power factor", where the current lags the voltage (like an inductor). This is primarily the result of having a lot of electric induction motors - the windings of motors act as inductors as seen by the power supply. Capacitors have the opposite effect and can compensate for the inductive motor windings. Harmonics present on the electrical system make correction methods for poor power factor more complex and expensive. Traditionally, capacitors are installed to improve power factor, thus increasing system efficiency and usually resulting in some form of savings on the monthly electrical bill. While capacitors do not generate harmonics, they can interact and magnify harmonic levels through a condition called resonance, increasing both harmonic current and voltage distortion levels.

SCR rectifiers present a variable power factor to the utility. Typically, the lower the load is the lower the power factor that is presented to the utility and the more power the utility must supply. Generally, at a 30% load the power factor is 0.6 or less. As the load approaches full load the power factor will approach 0.8. Factors that affect these values are input voltage (the higher the voltage the lower the power factor) and the construction of the output inverter.

IGBT rectifiers present a 1.0 pf to the utility independent of load and input voltage. This means that there is no phase shift between voltage and current and thus no reactive power is required from the utility. This means that there are no additional losses at the utility power distribution center and the utility feeder cables. The required current is as low as physically possible. This results in lower operating costs for the units. This will increase the system efficiency (minimize the losses of the input power feeder run) and will not create any problems with any other loads that use the same feeder subsystem.
5 Commutating gaps (High spike voltages)

Due to the higher switching frequencies of the IGBT’s, there are no switching/commutating notches (see the blue trace below and the oscilloscope screen capture) of the input voltage. The SCR design requires a short time when two phases are both on. This causes a momentary short circuit which tends to collapse the voltage waveform which causes the notch. This “noise” is sent back to any equipment that is being powered by the same utility source. Without proper filtering, this “noise” can damage electronic circuits and shorten the life of the equipment. Because the commutating gap also distorts the incoming power waveform, it requires the utility to provide more energy to compensate for the line losses. This results in higher operating costs for these SCR units.

Figure 11: Commutating gaps (principle – measurement)
6 System efficiency

Typically, specifications require a minimum efficiency value for a new SSFC. This is done with the assumption that a more efficient unit will cost less to operate over its life time. There are several problems with this approach.

First, efficiency values are typically given at full load. Most units do not operate at full load, most of the time they operate at 20% – 60% of full load. All units are less efficient at these load ranges. Therefore, efficiency values should be requested for 25%, 50% and 100% of full load for all units being considered for purchase.

Second, units with high harmonic distortion, like SCR rectifiers, affect the efficiency and lifetime of upstream components. High values of harmonic distortion cause increased voltage drops, especially in long cable runs. Transformer losses also increase and they operate at higher temperatures, which, over time degrade their insulation and increase their losses as well.

A cables voltage drop is affected by its impedance. Typically, we just consider the resistance portion of the impedance in calculating the voltage drops. However, this ignores the effect of harmonic distortion in increasing the reactance effect due to its influence at higher frequencies. The formula for determining the total voltage drop is:

\[ V_{td} = \sum (I*R*\cos\varphi + I*\omega*L*\sin\varphi)*\text{Length} \]

(Cos \( \varphi \) is the power factor and \( \varphi \) is the frequency) Typically, the fundamental frequency (50 or 60 Hertz) is predominant at low THD. However at higher THD values i.e. the 5\(^{th}\), 7\(^{th}\), 11\(^{th}\), 13\(^{th}\) harmonics of the fundamental, significant reactive current (the second half of the equation) is added and the voltage drop of the cable increases for all loads. The resistance (the first half of the equation) will rise at higher frequency also, because of the so called skin effect and will also increase the voltage drop. There is a similar affect on any upstream transformers.
The total system efficiency is the product of all of the efficiencies of the components of the system. \((\text{SSFC efficiency}) \times (\text{Cable efficiency}) \times (\text{transformer efficiency}) \times (\text{choke efficiency})\). The SSFC efficiency is only a part of the total system efficiency and it varies as a function of load. The cable and transformer efficiencies also vary as a function of the load, the power factor and the THD of the SSFC. Therefore, an SSFC with a lower efficiency but higher input power factor and lower THD will be the better unit to have when considering the total system efficiency.

7 No break power transfer capability

Most of the newer aircrafts, especially the wide body aircraft require a so called no break power transfer. During this transition phase, the SSFC and the internal auxiliary power unit (APU) of the aircraft are working in parallel to prevent any interruption of the power while switching over from internal power to external power. Since there is no precise synchronization and no load sharing / load transition regulator in place, the APU could feed some power back into the SSFC (reverse power).

SSFC’s with SCR rectifiers contain a risk that some components might be damaged during a reverse power condition. In this case, additional hardware (chopper with resistor etc.) must be used to “burn” the reverse power, since it can not be transferred to the utility directly. Even with additional hardware, the inner components are stressed by higher voltages during the transition phase. This higher stress and a number of additional components will decrease the reliability of these units.

SSFC’s with IGBT rectifiers will transfer the reverse power directly to the utility and thus do not need any additional hardware. Since no components are stressed by higher voltages created by the reverse power the reliability of the unit is not decreased and there isn’t any additional risk of malfunction.
8 Conclusion

In conclusion, while 6-pulse SCR rectifier SSFC units are slightly cheaper than IGBT rectifier SSFC units, they have some significant drawbacks due to their effect upon the total system. As energy prices continue to increase and power quality considerations and system reliability become more important, the construction of the input rectifier becomes a more important factor. IGBT rectifiers will optimize the energy consumption of the system and will reduce long term operating costs providing users payback within a short time. The long term investment for IGBT rectifiers is secured by eliminating the risk of “electrical pollution” and the negative influence to any other equipment on the same power system. In addition, they can handle reverse power conditions without any decline in the operating life time.