



Active front end drive technologies

Why active front end drive technology with DC bus capacitors is superior



- Active front end technologies with and without DC bus capacitors mitigate harmonics but with different levels of performance
- This paper will show how an active front end drive with DC bus capacitors is a better choice, especially for critical applications.

Active front end drive technologies

For improved harmonic mitigation

Active front end drive technology is recognized by many in the industry as the best technology for overcoming harmonic challenges. This paper details two hardware solutions used for active front end drives.

Harmonic mitigation and variable frequency drives (VFDs) are two topics often tied to each other. Non-linear loads, such as VFDs, generate harmonics. Electrical systems with high levels of harmonics may encounter issues, such as unstable operation of stand-by generators. Reference ABB document [Harmonics in HVAC applications](#)¹⁾ for more information on harmonics, problems caused by harmonics, and the many solutions available for cleaning up harmonics. Of all the solutions recognized, active front end (AFE) drive technology is widely considered the best overall harmonic mitigation technology.

There are two different AFE drive hardware designs available today, providing two different levels of performance.

- AFE designs that utilize DC bus capacitors.
- AFE designs that do not use DC bus capacitors.

Removing the DC bus capacitors from a drive may potentially lower the cost. However, most of the savings will likely be offset by the cost of other necessary hardware changes. From a performance perspective, removing the DC bus capacitors creates significant output voltage, harmonic mitigation, power factor, and power loss ride-through limitations within the drive. As an example, the DC bus capacitorless AFE drive may only produce 92% (or less) output voltage when it operates in low harmonic mode. These performance issues are only applicable for AFE drives that do not utilize DC bus capacitors. They do not apply to designs with DC bus capacitors.

The intent of this document is to use actual test data to educate the reader about the hardware and performance variances between the two AFE designs. For the purpose of this document, an AFE drive with DC bus capacitors will simply be called an AFE drive. An AFE drive with no DC bus capacitors will use the industry technology term matrix converter.

— Active front end drives with DC bus capacitors (AFE drives) and without DC bus capacitors (matrix converters) both mitigate harmonics, but with different levels of performance.

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AFE drive with DC bus capacitors

An AFE drive converts AC to DC, and then switches the DC back to AC, like a traditional 6-pulse VFD. The major difference between a 6-pulse and AFE drive is how it converts the AC to DC, and the hardware used to make this conversion. This hardware design has been available in the HVAC market for over 20 years. Figure 1 is a simplified hardware topology of an AFE drive and the differences between a 6-pulse and AFE drive are marked in the figure. Those differences include:

- Insulated Gate Bipolar Transistors (IGBTs) replace the diode-based rectifier that converts voltage from AC to DC. The IGBTs turn on and off very quickly, creating a smooth AC current waveform into the drive.
- An LCL circuit is installed before the front end IGBTs. This LCL filtering cleans up any high frequency noise caused by the IGBTs.
- A contactor drops out the LCL filter while the drive is not running the motor.

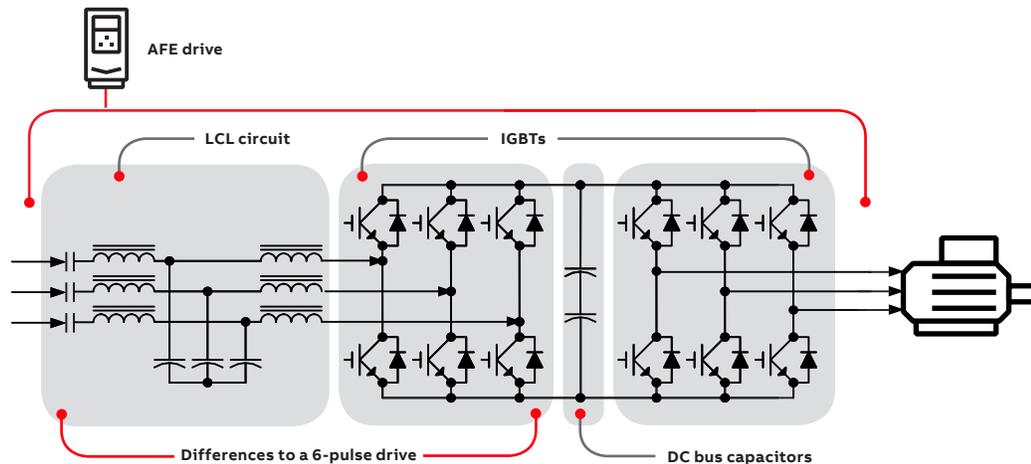
Matrix converter without DC bus capacitors

Figure 2 is a simplified hardware topology of a matrix converter. A matrix converter uses nine sets of IGBTs to switch line power directly to the motor. Each set is made up of two IGBTs that control voltage/frequency to the motor. A matrix converter is an AC-to-AC conversion and is a relatively new design available to the HVAC market. This style of drive uses an LC circuit in front of the drive to clean up any high frequency noise caused by the IGBTs. Table 1 summarizes the differences between these two technologies.

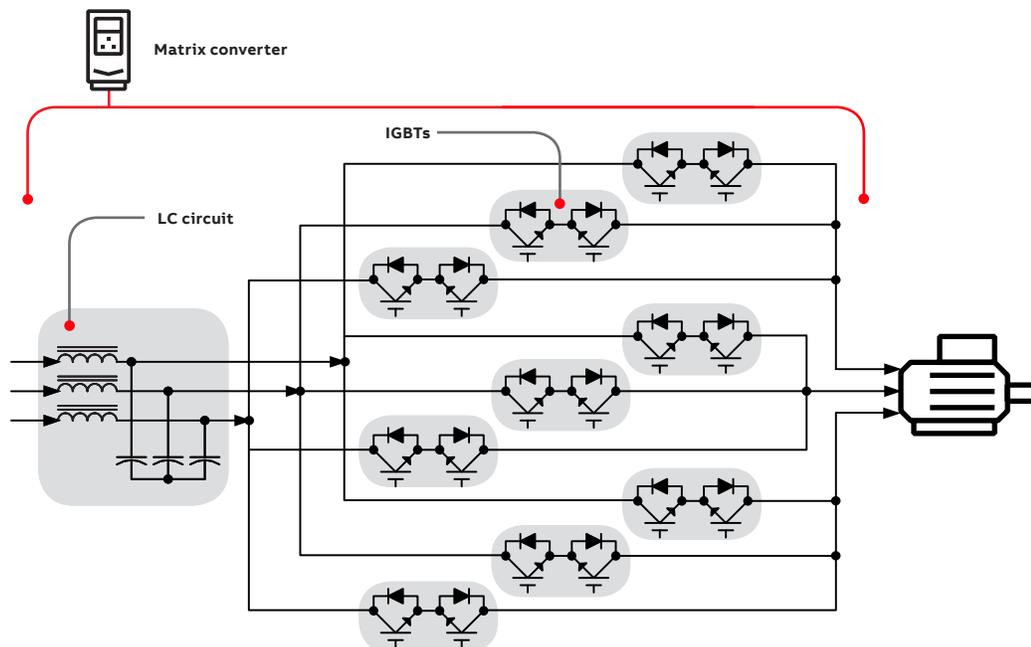
Table 1: Differences between an AFE drive and matrix converter

Differences	AFE drive	Matrix converter
DC bus capacitors	Yes	No
Number of IGBTs	12	18
Filter type	LCL	LC
LCL contactor	Yes	No

01 A simplified hardware topology of an AFE drive



02 A simplified hardware topology of a matrix converter



Matrix performance limitations

The matrix converter has multiple performance limitations. These limitations are related to output voltage capability, harmonic mitigation, power factor, and power loss ride-through. A matrix converter is also lacking features that AFE drives have, such as the ability to maintain the output voltage during an input line sag. The following sections outline the matrix converter limitations, discuss why these limitations are critical, and analyze how they compare to a traditional AFE.

Output voltage capability

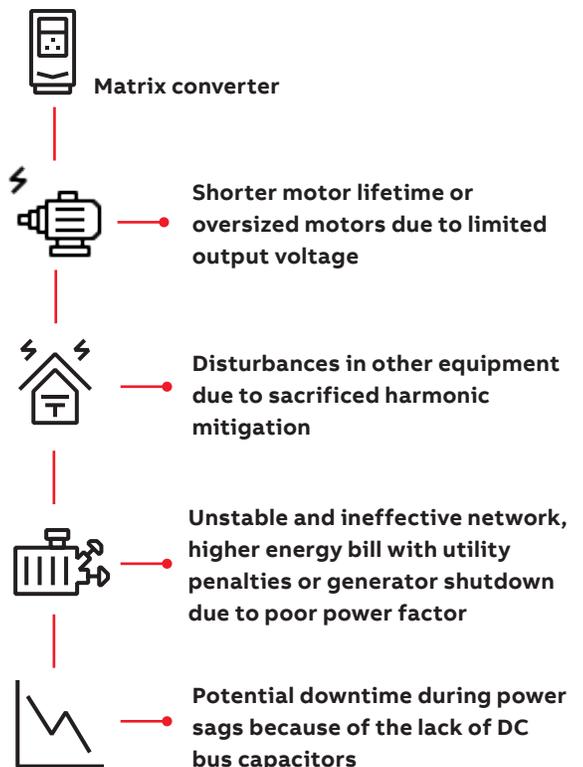
Most VFDs produce an output voltage that is equal to the motor nameplate voltage while operating at full speed. Motors require full voltage to achieve rated torque at full speed at rated Amps. Motors that do not receive full voltage are not able to produce rated torque at full speed unless the motor draws extra current to compensate for the lack of voltage. During this operating condition of drawing additional current, the motor will likely run hotter and thus shorten the operational life of the motor. To achieve rated torque and avoid overheating motors they need to be oversized.

A matrix converter can only produce full output voltage in select operating modes. The output voltage is limited because the matrix converter is modulating the line voltage instead of a DC bus voltage. The power factor performance is also dependent on the operating mode selected. A matrix converter typically has three independent operating modes while operating at full speed:

- Maximum output voltage (limited harmonic mitigation)
- Low harmonic (limited output voltage)
- Pass through (poor power factor)

For comparison, an AFE drive has a single operating mode that provides optimum harmonic mitigation performance while still providing maximum output voltage to the motor at full speed.

The following sections show the results of tests we conducted comparing an AFE drive and a matrix converter. Both drives are rated at 20 HP at 480 V and each of them was run on the same 20 HP, 23.5 A, 460 V, 1765 RPM, 60 Hz, 86% PF motor in an ABB laboratory. During each test, the motor was loaded to 100% torque at full speed. The calibrated measurement equipment consisted of a Hioki PW 3198 power analyzer, a Fluke 87V multimeter, Fluke 190-204 oscilloscope, and Fluke 337 current clamp. The input line voltage was a balanced 480 V three-phase line, unless specifically identified otherwise in the following sections. The matrix converter was tested in all three of its operating modes.



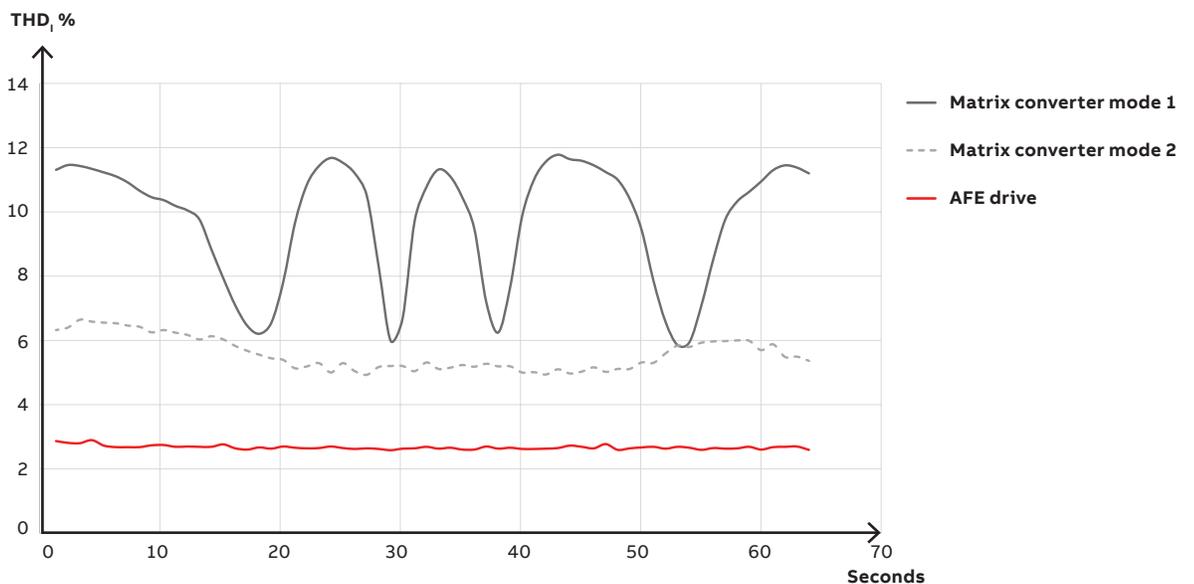


Matrix converter operation mode 1 - maximum voltage

In this mode, a matrix converter can produce full motor voltage at full speed. This mode would be the typical operating mode of a matrix converter to avoid the undesirable scenario of starving the motor of voltage at full speed. However, harmonic mitigation performance is sacrificed in this operating mode.

Total harmonic current distortion (THD_i) performance measured at the input terminals of the matrix converter is shown as mode 1 (dark gray) in Figure 3. This graph shows that the THD_i oscillates over time and reaches levels over 11%. This oscillation is unique to matrix converters, as other drive designs have stable THD_i performance without the high momentary peaks. The average matrix converter THD_i during this test was 9.4%. As a comparison point, the broadly accepted industry standard benchmark for low harmonic drives is 5% THD_i, based on applying the most stringent IEEE 519 system standard directly to the drive. The average harmonic signature of the matrix converter is almost double that of a low harmonic drive.

Figure 3: Total harmonic current distortion comparisons



03 Total harmonic current distortion comparison between a matrix converter's mode 1, mode 2 and AFE drive

Matrix converter operation mode 2 - low harmonic mode

In this mode, a matrix converter can produce approximately 5% THD_i at full speed. However, maximum output voltage to the motor is sacrificed in this operating mode. This mode is advertised as a low harmonic mode, but this mode is not always used in practice because of the output voltage limitations.

THD_i performance measured at the input terminals of the matrix converter is shown as mode 2 (dashed light gray) in Figure 3. This graph shows that the THD_i also oscillates over time and reaches levels near 7%. The average THD_i during this test was 5.6%.

Operating mode 2 does not allow full output voltage to the motor while operating at full speed. During this test, the matrix converter was only able to output ~88% of the input line voltage to the motor. On the 480 V line this resulted in 422 V being applied to a 460 V motor, while the motor was at full speed. This operating condition starves the motor of voltage.

The matrix converter's inability to provide 460 V in this operating mode is due to the lack of a DC bus. Starving the motor of voltage at or near full speed/load conditions causes the motor to draw more current, which in turn causes heating and shortens the life of the motor.

We conducted additional tests on mode 2, using a line voltage of 470 V and 460 V, to simulate other real world operating conditions. Table 2 indicates that the output voltage was still approximately 88% of the input voltage, but the motor current continued to increase well above the motor's 23.5 A rating. A Fluke 87V in low pass mode (also with data values verified with a Fluke 190-204 oscilloscope) set up to record VFD output voltage, was used to record drive output voltage. The use of separate metering was required due to discrepancies between the voltage displayed on the matrix converter's control panel (441 V) and the actual output voltage (422 V).

These test results show that using a matrix converter as a low harmonic drive requires additional design coordination by an engineer. The motor must be oversized for the application. Even with the matrix converter fed from the ideal 480 V nominal line, the motor drew 1.5 A (6.4%) over its nameplate rating. In the case of a project site with a sustained lower line voltage, such as 460 V, the motor consumed 2.3 A (9.8%) more current than the motor was rated to handle. Once a motor is oversized to allow the matrix converter to operate in low harmonic mode, the motor will likely operate at a less efficient operating point.

Table 2: Motor current consumption based on input voltage

Input voltage (V)	Motor shaft load (%)	Matrix converter (mode 2)		AFE (active front end) drive	
		Output Voltage to the Motor (V) Fluke 87V	Motor Current (A) Fluke 337	Output Voltage to the Motor (V) Fluke 87V	Motor Current (A) Fluke 337
480	100	422	25	459	23.5
470	100	412	25.1	459	23.5
460	100	409	25.8	459	23.5

Matrix converter operation mode 3 - pass-through

In this mode of operation, a matrix converter produces full motor voltage by locking specific IGBTs in an "on" state. This results in passing the line power directly to the motor, like a bypass circuit. In this mode, the motor would run at full speed only, as variable speed is not an option while this mode is active.

The benefit of this mode of operation is that the matrix converter can provide full motor voltage and low harmonics. However, there are multiple negatives to this mode, the biggest issue being power factor.

Mode 3 resulted in a 0.89 power factor when measured on the input of the matrix converter. The 0.89 value is only a small improvement over the motor's rated power factor of 0.86. In the United States as example, many utilities charge a power factor penalty at levels below 0.90, so in this mode of operation the matrix converter is contributing to power factor penalty. In comparison, an AFE drive maintains unity power factor while operating at full speed.

Another negative to this mode relates to energy savings. Mode 3 may be used to compensate for the output voltage limitations of mode 2. As a result, this mode is often engaged at frequencies just below 60 Hz. As an example, let's assume this mode is engaged at 57 Hz, which is 95% speed. Using the Affinity Laws as a reference, operating a variable torque pump/fan at 95% speed consumes only 86% power. In this example, if the application only required 95% speed, but mode 3 was engaged, there would be 14% more power consumed than necessary.

Mode 3 has financial impacts in both power factor and energy savings. Mode 3 is not recommended for HVAC applications that use drives for precise flow control or energy/cost saving purposes. This mode is better suited as a replacement for select applications that use reduced voltage soft starters but require certain features of a drive.



Power factor control

A drive's true power factor has a direct impact on a building's overall power factor. The matrix converter's mode 3 has a lagging power factor as described in the previous section. Modes 1 and 2 have a leading power factor at all speeds. The matrix converter also has a leading power factor while not running a motor, as the capacitors in the LC filter are still connected to the building's electrical system. Leading power factor in an electrical system is a concern because it can lead to instability with stand-by generators or cause voltage resonances.

A matrix converter cannot achieve a unity (1.0) power factor and the leading power factor value varies based on load. Figure 4 shows the measured true power factor of the matrix converter and the AFE drive.

An engineer should coordinate with the generator supplier on any systems with a high number of matrix converters and/or other sources of leading power factor. In addition to the power factor coordination concerns of the generator, an engineer must also verify the overall system is designed such that there would be no regenerative power fed back to a generator from the matrix converter(s). Generators can handle very little regenerative power before their internal parasitic loads are overcome, and the generator shuts down to protect itself.

Power loss ride-through

While in most locations the utility power supply is stable, power fluctuations do occur. During these brief power sags, there is an industry desire to have the drive maintain control of the motor. This is

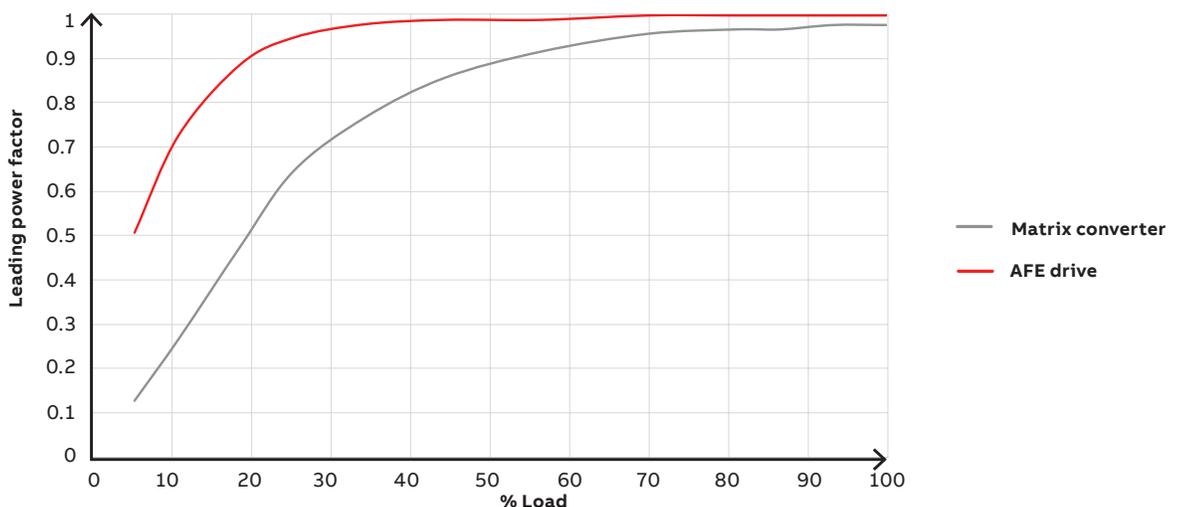
especially important in critical applications and/or facilities such as hospitals and data centers.

The phrase "control of the motor" is important when discussing power loss ride-through. Only keeping the control panel/logic of a drive powered is not a power loss ride-through. A brief power fluctuation should not result in down time, where the motor is coasting to a stop and needs to be restarted. When control of a motor or motors is lost, a drive may perform a "flying-start" function to catch the coasting motor or motors. Executing a "flying-start" function may not be achievable on some multiple motor applications. Multiple motor applications reinforce the importance of being able to control the motors during power loss situations.

To support a power loss ride-through feature, a drive must have the ability to store energy. Capacitors in a drive are used to store energy. The capacitors can provide a short-term power loss ride-through to keep control of a motor without interruption. The length of the ride-through can be extended in applications that are high inertia. An industry standard for power loss ride-through capability is SEMI F47, which tests devices by reducing the input voltage for varying periods of time. Most AFE drives (with DC bus capacitors) on the market meet the SEMI F47 standard.

Matrix converters do not have DC bus capacitors, thus cannot store meaningful energy. Matrix converters do not have power loss ride-through. Although with creative marketing, matrix converters are known to support control power loss ride-through. This simply means the control panel/logic stays powered during a brief power outage, but this feature generally provides no ability to maintain control of the motor during a power fluctuation.

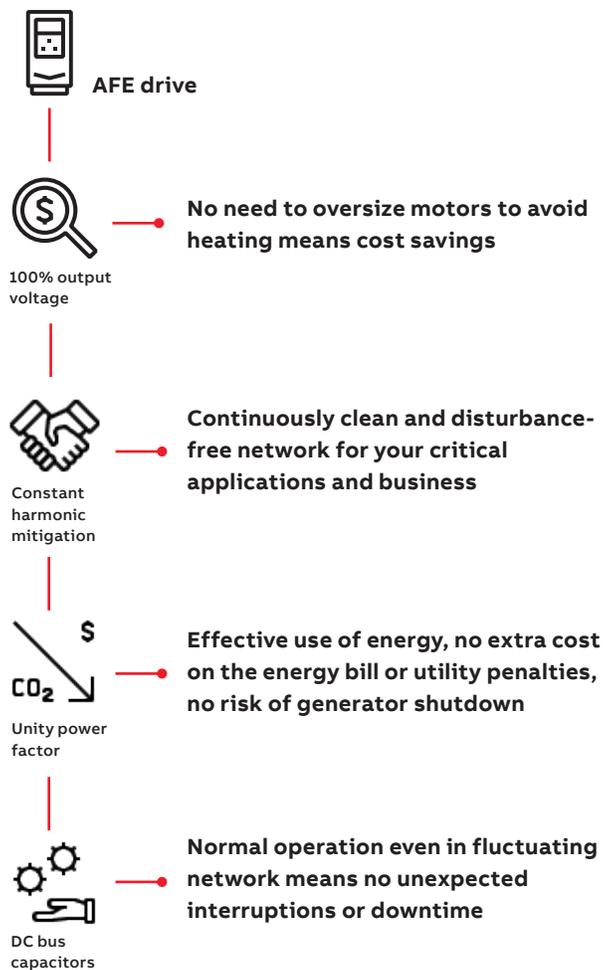
Figure 4: True power factor



AFE test results

Comparison to the matrix converter

Unlike a matrix converter, an AFE drive does not require three different operational modes for controlling harmonics. There are several major performance differentiators between the AFE drive and matrix converter. The most significant differentiators include harmonic performance, output voltage capability, motor current draw, and power factor. To ensure consistency, the AFE drive was tested under the same conditions as the matrix converter.



The key performance takeaways from our testing are:

- DC bus capacitors allow the AFE to achieve maximum output voltage while resulting in less than 5% THD_i at the drive input terminals. The average AFE THD_i of 2.7% was significantly better than the matrix converter's levels of 9.4% (mode 1) and 5.6% (mode 2). Reference Figure 3.
- AFE harmonic performance is stable compared to the larger harmonic oscillations of the matrix converter. Reference Figure 3.
- The AFE maintains unity or near unity 1.0 power factor down to 40% load. The matrix converter modes 1 and 2 do not achieve unity power factor, and have an always leading power factor, that becomes noticeably leading below 75% load. Reference Figure 4. The matrix converter mode 3 has a poor 0.89 lagging power factor.
- The AFE design includes an input contactor to disconnect the LCL filter from the electrical system while the drive is not running. The matrix converter does not have this contactor thus the LC filter creates a leading power factor even while the drive is not running.
- The AFE voltage boost feature allows output voltage to be maintained at/near motor nameplate during low input voltages. The AFE provided 459 V output to the motor with an input line of 460 V input to drive. The matrix converter low harmonic mode (mode 2) could only output a maximum of 422 V under the same operating condition. Reference Table 2.
- The AFE drive was able to keep the motor's current draw at the motor nameplate rating of 23.5 A, even with a low 460 V input to the AFE drive. The matrix converter low harmonic mode (mode 2) caused the motor to exceed its nameplate current rating by 6.4%, even when the matrix converter was fed from an ideal 480 V line. Reference Table 2. Applying the AFE drive to a low line condition was less stressful on the motor than a matrix converter applied to an ideal line condition.

Marketing of matrix converters may not tell the whole story

The performance limitations of matrix converters as discussed in this paper are often not explained in matrix converter sales literature. Be skeptical of marketing documents supporting matrix converters. Marketing documentation may advertise the best features for each operating mode, yet fail to disclose that the matrix converter cannot achieve all these features at once. Documentation on a matrix converter may advertise the drive as:

Low harmonic or IEEE 519 compliant

The documentation may not state that this compliance is valid for mode 2 operation, and in mode 2 the drive will not be able to provide full nameplate voltage to the motor. Mode 2 could result in premature motor failures, thus the matrix converter may not be commissioned in this mode. Instead, the drive may be commissioned in mode 1. If this occurs, the matrix converter is no longer considered a low harmonic or IEEE 519 compliant drive.

Pass-through mode or energy savings mode (also referred to as mode 3 in this document)

The documentation may fail to mention the poor true power factor of this mode, which could contribute to power factor penalties from the utility. There could be lost energy savings because matrix converter only runs at 60 Hz full speed in this mode. In many applications, mode 3 has the potential to cost a building owner more money than this mode will save.

Near unity power factor and 0.98 displacement power factor

The documentation may not mention the matrix converter's near unity power factor is actually a slightly leading power factor. Also, the document may not mention that these power factor values are only applicable in mode 1 and mode 2. Mode 3 power factor is worse.

Control power loss ride-through

The documentation may not describe the fact that as soon as utility power is lost, the drive is unable to control the motor(s). Because the control panel is still lit, the user may incorrectly believe the drive is still controlling the motor.

Contactless bypass

The documentation may omit that this bypass mode cannot be used as an emergency backup upon matrix converter failure. Traditional bypasses in HVAC drive systems use contactors to provide a backup in case of drive failure.

Conclusion

Active front end drives are widely considered as the best technology for low harmonic drives. There are two hardware platforms of AFE drives, with and without DC bus capacitors. The version without DC bus capacitors, known as a matrix converter, has several limitations that are unique to that hardware design. Those limitations include output voltage, higher harmonic levels, higher current draw from the motor, power factor, and power loss ride-through capability.

Conversely, an ABB AFE drive, also known as an Ultra Low Harmonic (ULH) uses DC bus capacitors. This AFE design has one operating mode that does not have the limitations mentioned earlier tied to a matrix converter without DC bus capacitors. This operating mode is low harmonic IEEE 519 compliant, capable of producing full motor nameplate voltage, has unity power factor, and has a true power loss ride-through, all while supporting other features, such as programmable power factor control and a voltage boost feature for low input line conditions. The performance limitations of matrix converters, as outlined in this document, do not apply to an ABB AFE drive. An ABB AFE drive may be an ideal solution in your application to limit harmonics in electrical systems, allowing a motor to achieve peak performance and greater longevity.





ABB Inc.

16250 W. Glendale Drive
New Berlin, WI 53151
(800) 752-0696

ABB Inc.

800 Hymus Boulevard
Saint-Laurent, QC
H4S 0B5

abb.com/drives

