Advancing the Practice of Electrical and Electronics Engineering in Industry

# IEEE Industry November/December 2019 Vol. 25, No. 6 www.ieee.org/ias Application

# Advancing Industry With Motors and Drives





# IEEE Industry Applications Magazine

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Advancing the Practice of Electrical and Electronics Engineering in Industry

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Revving up for an exciting future for motors and drives.

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By Manish Verma, Neeraj Bhatia, Scott D. Holdridge, and Todd O'Neal

# Isolation Techniques for Medium-Voltage Adjustable Speed Drives

DRIVE TOPOLOGIES FOR MAINTAINING LINE-SIDE PERFORMANCE

COMPRESSION AND PUMPING APPLICATIONS REPRESENT a majority of all rotating machinery in modern industrial plants. In the past two decades, electric motors have been replacing turbines as the prime mover of choice for large rotating equipment at an increased rate. The use of electrically driven equipment is widespread even for critical applications. As semiconductor technology evolves, adjustable speed drives (ASDs) gain favor as the best option for both motor starting and speed control. Volume, pressure, and flow are adjusted by varying the speed of electric motors, even in motors that are larger than 50,000 hp. Multiple medium-voltage (MV) ASD topologies exist today that offer excellent motor performance. One of the key topics of discussion among specifiers and end users concerns the effects of ASDs on the utility line. Several methods for improving line-side performance use incoming isolation transformers, but some do not. It is often not clear when

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drive isolation transformers (DITs) should be used and which converter topology should be employed. This article is a guide to drive isolation techniques and major types of converters for various topologies of MV ASDs. It briefly explores the theory, advantages, and disadvantages of each configuration and application with considerations for selecting the optimal drive isolation technique.

#### Focusing on the Line Side

For more than 30 years, ASDs, both low voltage and MV, have been applied in plant processes. Through progress in reliability, ASDs have become essential for improved productivity and efficiency and are increasingly preferred over mechanical systems such as engines, turbines, fluid couplings, and throttling valves as the prime mover and source of flow control. The rapid advancement of power semiconductor devices such as the silicon-controlled rectifier (SCR), insulated-gate bipolar transistor (IGBT), gate-controlled thyristor (GCT), and symmetrical gate-commutated thyristor (SGCT) has made this possible. However,

with the multiplicity of topologies available, the end user or specifier is challenged in deciding which one to employ.

Line-side converter topologies have progressed significantly over the past 20 years. Challenges remain in understanding, specifying, evaluating, and installing the appropriate converter topology and isolation technique for a given application and power delivery system. In recent years, several papers have been published on techno-commercial bene-



**FIGURE 1.** The basic building blocks of an ASD system.

fits, application and installation considerations, factory acceptance testing, cooling systems, and other factors in applying an MV ASD and motor for petrochemical applications [1]. A holistic evaluation of the drive isolation techniques and converter topologies, and their influence on the utility, in particular, is pertinent to the overall evaluation and procurement strategy. In this article, we hope to aggregate and share this information, which can be used to gain an understanding from inside the ASD and make informed decisions that best suit an application.

#### Building Blocks of an ASD System and Applicable Scope

Figure 1 shows the major building blocks of an MV ASD system. Depending on the ASD topology and the manufacturer, some blocks may not be present [2]. The scope of this article is limited to the transformation and the acto-dc conversion sections of the ASD. The latter section is hereafter referred to as the *converter* or *line-side inverter*. Note that *line side* and *utility side* can be used interchangeably. This article covers ASDs within the ranges depicted in Table 1.

#### **Converter Topologies**

ASDs convert fixed voltage and fixed frequency available from the utility provider to adjustable voltage and frequency. This allows motor speeds to be controlled and process outputs to be adjusted to the desired flow and pressure. Flow is linearly proportional to speed; hence, a change in speed results in change of flow. The ASD goes through a two-step power conversion process. First, it converts the fixed frequency (60/50 Hz) ac waveform into dc (0 Hz) that feeds an energy storage element such as an inductor or a capacitor. This is called rectification. Next, the stored energy is converted from dc back into ac that powers a motor. This is called inversion. The rectification section, commonly known as the converter, provides two important functions: it produces a steady dc source for the load-side inverter, through either an inductive current source inverter (CSI) or capacitive voltage source inverter (VSI) dc link, and, it provides a high-power-quality interface to the grid [3].

#### Types of Converters

Two main types of converters are available: passive and active. Passive converters use a combination of power diodes to accomplish full-wave ac rectification. The simplest diode converter is a six-pulse configuration, as shown in Figure 2. ASDs that employ diodes as their main rectification devices are nonregenerative. Almost all lowvoltage drives and many MV drives have a diode front-end converter. This is due to the simplicity in design. In applications such as pumps and compressors, there is no need for regeneration, so a diode converter is acceptable.

Active converters use power semiconductor devices such as IGBTs, GCTs, SCRs, and SGCTs to produce fullwave ac rectification. Transistor/thyristor devices such as IGBTs and GCTs can be controlled independently of the utility waveform, and their effect on line-side performance can be controlled by the drive itself. Other devices such as an SCR in a load-commutated inverter (LCI) drive depend on the utility waveform to commutate. Figure 3 shows an active front end (AFE) converter ASD. Active converters are well suited in highly regenerative applications such as conveyors, hoists, and hot gas expanders, where power can flow in either direction, allowing for dynamic braking and energy savings. Some AFE drives use an inductancecapacitance or inductance-capacitance-inductance filter to eliminate current harmonics.

#### Table 1. Applicable scope of this article

Parameter	Value
Power level (hp)	500 to ~12,000 hp
Voltage range (kV)	MV 1.0–6.9 kV
Drive type	CSI (pulsewidth modulation-based or LCI-based) or VSI
Motor type	Induction
Cooling	Air or liquid
Driven equipment	Variable torque and constant torque such as pumps, compressors, fans, extruders, mixers, and hoists



FIGURE 2. A six-pulse diode rectifier.



FIGURE 3. An IGBT-based AFE converter.



**FIGURE 4.** The line-side current waveform of a typical six-pulse diode-based converter with an estimated current total harmonic distortion  $(I_{THD}) \sim 35\%$ .

#### Effects of Converter Topologies on the Line Side

One of the functions of the line-side converter is providing a high-power-quality interface to the grid. However, since converters use power semiconductor devices, there are side effects. The switching process of these devices is nonlinear. Nonlinear loads do not shift the current waveform; the waveform is distorted (see Figure 4). The distorted waveform produces harmonic currents that are reactive in nature and provide no useful work. Some of the adverse effects of rectifiers used in ASDs are as follows:

- distorted voltage waveform from harmonic currents reflected back to the utility
- low utility-side power factor due to distorted reactive power component and subsequent power factor penalties
- harmonic heating of the upstream transformer
- erratic operation of equipment on bus common to the ASD.

#### Mitigation Strategies for Converter Line-Side Effects

#### General

Multiple factors are critical to the design and performance of MV ASD converter sections. Three are considered most significant: commonmode voltage, harmonic distortion, and line-side power factor control. To allow for system upsets, the drive should be designed to withstand the

effects of transient voltage surges, spikes, and short circuits. Voltage and current transients can affect the reliability of a drive. Auxiliary equipment such as input isolation transformers, line reactors, and filters are used to mitigate voltage transients and distortion.

Common-mode voltage, also called *neutral point shift*, is voltage common to multiple conductors of a threephase load (such as a motor) that appears at the neutral point. Common-mode voltage is harmful to the insulation of the drive output, motor leads, and stator windings. The amount of common-mode voltage that shows up at the motor end is largely dependent on the type of drive isolation technique used.

Harmonic distortion (the measure of harmonic currents flowing back to the power distribution system during drive operation) is undesirable and regulated at the point of common coupling (PCC) per IEEE 519 [7]. Excessive harmonic distortion can disrupt proper operation of equipment on the line side of the converter.

Power factor, the ratio of real to apparent power, affects the operational cost and sizing of system components upstream of the ASD. As the power generation mix

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of the nation changes from a fossil fuel-based system to renewables, the grid is losing electrical inertia due to a large number of synchronous generators being retired in coal-fired plants that provided the necessary reactive power to support the voltage. It is critical that downstream equipment such as MV ASDs operate at near-unity power factor or even improve the power factor at the local bus level.

Two primary isolation techniques exist for MV ASDs: 1) isolation transformers with passive front ends (PFEs) or AFEs and 2) transformerless AFEs (TAFEs). Each topology presents individual advantages and disadvantages.

As a limitation to the scope of this article, the term *AFE* is understood to describe an ASD with a converter with self-commutated switches. The semiconductor devices of an AFE converter may be switched on and off with a control signal and associated gating circuits, rather than requiring load or source influences for switching.

#### PFE Converter With Phase-Shifting DIT

A PFE with a DIT is a combination of a phase-shifting transformer and a multipulse rectifier. For the architecture shown in Figure 5, the power cell for each phase will receive a 24-pulse input. This topology cancels all harmonic frequencies below  $P \pm 1$ , where P is pulse count. Input transformers wound in a variety of configurations, either wye (zigzag, fork) or delta (extended delta, polygon), combine specific proportions of adjacent secondary windings to produce the designed voltage and phase shift. When current is balanced in each secondary of the transformer, harmonics from individual converters will cancel each other completely. This is never the case due to discrepancies in manufacturing, such as each converter having its own winding load imbalance (for example, there will be four three-phase windings per phase, resulting in a total of 12 secondary three-phase windings to feed a 24-pulse rectifier), variations in line-side voltage, and other system variances. A conservative estimate for the remainder of the canceled harmonic frequencies in the computation of total harmonic content is 10%. Power factor is not controllable in a PFE drive and will vary with motor speed and load. Although the displacement power factor for the MV drive can be high, approaching unity, the correct assessment of its power factor capabilities lies in determining the true power factor that includes the harmonic content of the line-side waveform. This is given by (1) and is usually a few percent lower than the displacement power factor:

True Power Factor = 
$$\frac{\text{Displacement Power Factor}}{\sqrt{1 + \text{THD}^2}}$$
. (1)

DITs for PFE drives have impedances of approximately 8–10%. This impedance mitigates the negative effects of short circuit current flow through the drive [5].

#### AFE With DIT

ASDs with an AFE and DIT utilize controllable semiconductor devices such as a GCT, IGBT, or injectionenhanced gate transistor (IEGT) in the converter section. For this drive architecture, an input transformer is used for drive isolation protective properties, but the active converter does not require multiple-phase-shifted inputs to cancel harmonics. Firing angle and conduction times are controlled, resulting in adjustable phase angle and dc bus voltage. This characteristic gives the AFE drive the ability to control both real and reactive power flow. When switched properly, the controller can reduce the creation of many low-order harmonic frequencies. The switching strategy of the AFE converter will greatly affect the line-side harmonic performance. Synchronous and asynchronous switching strategies are used in AFE drives. Both methods are designed for harmonic mitigation and power-factor control, but the result is achieved very differently. Asynchronous switching uses a fixed switching frequency for converter semiconductors. The switching frequency is ideally a high multiple of the line frequency, usually 10 times line frequency  $(10f_L)$ . Synchronous switching methods produce low-amplitude harmonic frequencies. Synchronous switching can be achieved several ways. Common is the sine-triangle method in which pulsewidth is determined through a comparison of a triangular carrier wave to a sinusoidal reference wave. Pulsewidth varies depending on the relative values of the two waves. Input transformer impedance is usually higher for AFE drives, often in the 15–20% range [6] and with a high k-factor rating. Figure 6 shows a typical circuit configuration of an AFE drive with isolation transformer.



FIGURE 5. A 24-pulse diode rectifier with phase-shifting transformer.



FIGURE 6. An AFE converter with a DIT.



FIGURE 7. A TAFE drive.

#### TAFE Drive

In the case when the line voltage matches the motor voltage, the input isolation transformer and all other transformers may be eliminated. This topology is referred to as a TAFE drive. In a TAFE drive, the input isolation transformer is replaced with an impedance in the form of a line reactor or inductor and, in some cases, a parallel input capacitance as well. So long as converter harmonic distortion is low, a line reactor can be sufficient for harmonic mitigation. The reactor cannot be eliminated altogether, as the impedance is necessary for the converter to operate properly when connected to a utility system. Because a line reactor does not alter voltage magnitude, load voltage must match system voltage. Common-mode voltage concerns are reduced through the proper switching and design of input inductor and capacitance. IGBT and SGCT semiconductors are most commonly used for this type of AFE drive. Switching methodologies are the same as AFE drives using an isolation transformer. Figure 7 shows a typical circuit configuration of a TAFE drive.

#### Transformerless Drive Isolation Techniques–Pros and Cons

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The substitution of cost of the phase-shifting transformer for that of a line reactor and reduced drive footprint and weight are advantages of a transformerless design. A line reactor will likely be smaller than a DIT of similar rating, and it is inarguably less complex than a phase-shifting input isolation transformer. It is likely that overall drive dimensions will also be reduced. This diminishment in size can provide a cost benefit through a reduction in the size of the enclosing power control building and can contribute to reduced installation cost.

Along with the theoretical advantages come limitations and concerns regarding the operation of a transformerless drive. Although this design is considered transformerless, it is not reactorless. An input inductor or reactor and, in some cases, capacitors are still required. This reactor contributes to the dimensions and weight of the drive. If no input impedance is added between the converter and power system, the power semiconductor devices are exposed to the utility and have no protection from voltage transients and spikes. Because the input is galvanically connected to the source, common-mode voltage may be elevated. Although common-mode voltage can be reduced by precise input reactor design, it is not eliminated, and transient voltage swings can reduce the life of motors and motor leads. An increase in motor lead insulation rating may be required. Applications such as offshore platforms, retrofits in existing motor control-center rooms, and installations starting and synchronizing single or multiple motors can benefit from this method.

#### Transformer Drive Isolation Techniques—Pros and Cons

Relative to drives of a transformerless design, the impedance of the DIT provides an increased rate of change of current (di/dt) and short circuit mitigating benefits. Because a DIT creates a separately derived system, where line and load are galvanically separated, commonmode voltage is reduced. This provides fundamental immunity to the damaging effects of ground faults on the line side of the drive. The DIT with a delta winding provides a path for triplen harmonics to circulate rather than returning to the utility. This circulation path reduces harmonic content. In this comparison, the tradeoffs for increased input impedance are cost, volume, and weight. Assuming there is no additional equipment required for a transformerless design, such as capacitor banks or snubbers, the footprint for a DIT-type drive is likely larger than that for a drive of a transformerless design. The theoretical benefit of a transformerless design over one with a DIT, including cost, is often reduced by the addition of capacitor banks and dv/dt or sine wave filters on the line and/or load side of the drive. When system voltage does not match load voltage, a power transformer is required on the primary, the secondary, or both. In such a case, it can no longer be considered a transformerless design.

#### Application Considerations When Selecting Line-Side Isolation Techniques

Investing time and resources in selecting and evaluating the appropriate type of converter topology, as well as the drive isolation technique and its impact on the power grid, is critical for the ASD to operate as intended. This is beneficial not only during startup but also when the ASD is fully commissioned and running.

## Considerations for an ASD Employing a Transformer Isolation Technique

The following are some of the application items to consider.

- Electrostatic shielding between the primary and secondary/tertiary windings is recommended so the capacitive coupling between windings is minimized. This blocks the transfer of surge or impulse voltage (such as high dv/dt induced by semiconductor switching operation) to the motor. It may be necessary to route the primary and secondary power cabling in separate trays to avoid any potential capacitive coupling between cables.
- 2) The specifying engineer provides the maximum and minimum short circuit level at the PCC, which is commonly at the primary side of converter transformers. While in the scope of the ASD manufacturer, the selected transformer impedance must take into account the converter's short circuit duty and voltage notch depth and the harmonic distortion it can expect to see from the rectifier section.
- 3) Because common-mode voltage is generated by the drive, the use of a DIT converter with the grounding drive output capacitor is common practice to transfer the common-mode voltage from motor to transformer to protect the motor. Therefore, it is necessary to confirm whether the transformer insulation is designed to withstand the common-mode voltage generated by the ASD. The application of a capacitor is also dependent on the output waveform generated by the ASD.
- 4) For an islanded power generation system, an excessive voltage drop may occur momentarily due to a high inrush current when energizing the converter transformer. It is necessary to coordinate with generator suppliers to determine whether a high inrush current to the DIT will result in operational issues. In many cases, the ASD can also be supplied with a precharge reactor built into the ASD that will limit the inrush current down to 1.2–1.5 per unit. Other precharge strategies also exist, such as using a low-voltage source to feed a precharge circuit that, in turn, feeds the secondary of the transformer before main power is applied or uses a low-voltage feed to charge the dc-link capacitors directly.
- 5) Foil-type or sheet-winding constructions are usually not considered acceptable to use in a converter isolation transformer.

- 6) When a fuseless converter design is proposed, isolation facilities (i.e., fused disconnector switches) at the transformer secondary/tertiary windings should be considered if a short circuit withstand time of the converter is lower than the fault-clearing time of the primary protective device for the DIT.
- 7) In a transformerless drive isolation technique, it is important to apply an input impedance in the form of a reactor between the ASD and the utility line.

#### Footprint and Weight

Depending on the topology employed, footprint and weight can have a significant impact in the overall selection criteria for a particular isolation technique. Transformerless drives by themselves are much smaller and lighter than drives with an isolation transformer. In fact, the absence of the transformer can reduce the overall footprint by 20-30% and the weight by 30-50% for the same voltage and current rating. This is especially attractive for applications where real estate is at a premium and every extra pound of weight adds logistics and install cost. Offshore applications, retrofits where space is limited, and applications where the drive will be used for starting purposes will benefit appreciably from a transformerless design. Transformerless isolation techniques often require a line-side reactor along with a filter, which could potentially eliminate all the efficiencies that were captured by choosing a transformerless drive to begin with. Table 2 shows a comparison of transformer versus transformerless drives rated at 4.16 kV and up to 140 A.

#### Heat Loss

Most modern MV ASDs reject 3–4% of the drive rating as heat. This heat is rejected to the air or water (in the case of water-cooled drives). Figure 8 shows a configuration of an ASD. While most of the heat is lost in the inverter section of the drive, approximately 30–40% of the heat loss (~1–1.5% of the overall drive rating) is contributed by the DIT and the diode-based ac–dc converter. For TAFE converters, the heat loss contribution from the ac–dc converter can be as high as 2% of the overall drive rating. This is because the converter section no longer uses a diode but, instead, employs power semiconductor devices that inherently have higher switching losses than diodes. Also, an input line reactor

## Table 2. The footprint and weight comparison between the transformerless and transformer ASD

Isolation Technique	Overall ASD Footprint (in²)	ASD Weight (lb)
Transformerless	3,720	6,500
Transformer	5,170 (~40% larger)	11,400 (~75% heavier)

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is needed for TAFE implementations, which contributes an additional 0.5%, bringing the heat loss on the front end of the drive to 2.5% plus the applicable heat loss in the inverter section. Eliminating the transformer completely does not necessarily reduce the overall heat loss of the ASD, as it is widely believed to. Nonetheless, by moving the transformer outdoors, there is an appreciable reduction in the indoor heating, ventilation, and air-conditioning (HVAC) requirement to cool the ASD, as indicated in Figure 9.



FIGURE 8. The typical heat loss distribution of an MV ASD. O/P: output; M: motor.



+US\$10,000 +US\$35,000

Net Difference in HVAC Requirements = 25% (~6.5 t)

**FIGURE 9.** A cost and installation parameter comparison of a 2.2-MW, 4.16-kV variablefrequency drive (VFD) with an integral DIT versus an outdoor transformer. Xfmr: transformer; Conv: converter; t: tons of cooling. (Used with permission from [4].) Specifiers who are evaluating the installation of a DIT outdoors should consider the additional cost and installation requirements. In [4], the authors provide a sequential comparison of the cooling requirements for ASDs that integrate the DIT as a part of the lineup to the requirements for ASDs that separate the transformer from the lineup. This is shown in Figure 9.

Usually, air-cooled drives rated over 3,000 hp and water-cooled drives tend to benefit from the transformer's being placed outdoors, given that the heat contribution from the transformer would otherwise be a significant addition to HVAC loading. When evaluating overall ASD efficiencies, it is equally important to include the efficiency of the drive, motor, harmonic filter (if necessary), auxiliaries, and cooling system. As per the IEEE 1566 standard, efficiencies are to be provided by the ASD manufacturer at 25, 50, 75, and 100% speed and load for variable torque or constant torque, depending on the project requirement.

Another option for eliminating the concern with heat loss is to specify outdoor-rated drives. Modern outdoor-rated drives are available from 500 to 3,000 hp.

#### *IEEE 519-2014: Recommended Practice and Requirements for Harmonic Control in Electric Power Systems Compliance*

IEEE 519 is commonly cited in MV ASD specifications. Ignoring it can result in a harmonic nightmare that is often very difficult to fix after the fact. IEEE 519 was first released in 1992 and revised in 2014. The latest standard revision has a very different focus, as it pertains to the system design only rather than the power converter equipment itself. The standard also clearly defines the

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PCC. In the 1992 version, the PCC was vaguely described and left to interpretation. Since several end users faced challenging harmonic issues when large MV ASDs were applied, eventually ASD procurement specifications required that the drive meet IEEE 519 I<sub>TDD</sub> limits as indicated in Table 10.3 of the 1992 standard. Most drives at 18 pulse and above and select AFE drives can meet the requirement without the need for the additional line-side filter at  $I_{TDD}$  of <5%, assuming the ASD is running at rated load, and the input voltage is fairly well balanced. However, the 2014 revision of IEEE 519 clearly defines the PCC as belonging to the high-voltage side of the service transformer for industrial users. This means that the harmonic measurements are done upstream of the MV drive. This clarity in defining the PCC was introduced because harmonic control is a shared responsibility between system owners (utility providers) and end users. The requirement for the MV drive meeting IEEE 519 at its input has become less strict. System impedance manipulation is addressed in IEEE 519-2014. It says that "users should not add passive equipment that affects the impedance characteristic in a way such that voltage distortions are increased" [8]. This implies that an MV ASD specifier should thoroughly understand the topology of the drive and verify whether line-side filters or active or passive capacitors within the drive during starting and running conditions will adversely impact the overall bus voltage or introduce voltage distortion.

#### IEEE 1566 Guidance on Specifying

The standard for performance for ac ASDs rated 375 kW and greater, known as IEEE 1566-2015 [9], is the most comprehensive performance standard for MV drive procurement. From an ASD line-side transformer and harmonics perspective, the data sheet in the standard asks for details on harmonics and input transformer to be filled out by the purchaser, as shown in Figure 10.

The ASD manufacturer is also required to fill out comparable sections in the data sheet when responding to an end-user inquiry. The sections in the standard that address line-side characteristics are the following:

- rectifier (5.4)
- source impedance device (8.0)
- harmonic performance (6.15).

#### Serviceability and Maintainability of Transformer Versus Transformerless Drives

Both types of drives require proper cooling, cleanliness, and internal and external electrical connections to maintain critical uptime and reliability. Whether transformer or transformerless, they require regular manufacturer-recommended preventative maintenance for critical reliability, as they are generally on critical primary production systems in plants. Transformerless drives are easier and less time-consuming to maintain, due to the

absence of the need to maintain a transformer and the associated hardware requiring testing. However, drives that use a transformerless solution commonly need more involved electrical maintenance in the testing of primary components in the converter section, since they are of AFE type and consist of IGBTs, SGCTs, IEGTs, and so on. In the case of transformer-style drives, one should note that these transformers can be either oilfilled indoor or outdoor construction and water-cooled or dry type, depending on the voltage/current rating and manufacturer. ASDs that use oil-filled transformers need periodic maintenance, similar to any other substation transformer. Items such as dissolved gas analysis, pressure, temperature, liquid level monitoring, cable connections, tank leaks, paint, and coatings will require attention. ASDs that use a dry-type isolation transformer are usually maintenance free, other than standard manufacturer electrical testing and cleaning. They are not maintenance free if they are water-cooled deionized water systems, which require inspection of all water connections, fittings, and hoses along with testing of deionized water conductivity as preventative maintenance, which includes water system pumps. Basic items such as checking torque marks, vacuuming, removing environmental contaminants, visual inspections, and electrical testing (meggering) should be generally sufficient. Both (dry type and oil filled) require confirmation of proper cooling and the operation of auxiliary blower systems on transformer and main power converter sections.

To plan for the unlikely event that the DIT needs complete replacement or repair, it is important to consider the amount of labor and time that would be required to access and remove the multiwinding transformer that is unique to the ASD drive. DITs are not generally stocked or readily available from the

Impedance versus frequency data sur	oplied at PCC? O Yes O No
Point of common coupling (PCC):	Voltage at PCC: V
Required telephone influence (I.T) at F	PCC:
Average Demand Current (IL):	
Other harmonic requirements:	
Harmonic Compliance to IEEE 519:	Yes O No
Harmonic Compliance to IEC 61000-3	3-6: O Yes O No
If 'No' to both of the above, state voltag	e THD requirement at PCC:
Input Transformer/Reactor (8.1.1	():
As per standard (8.1.2)	As per attached specification
O Location: O Indoor	Outdoor
Winding Material: O Cor	
Transformer Taps (8.1.3):	
O Yes O No	
If Yes: 0 +2.5% 0	±5% Other
Ear autoar colour is:	By Vandar O Other Specify
r or outdoor, colour is.	by render O outer, specily.

**FIGURE 10.** A snapshot of the relevant purchaser data sheet section in the IEEE 1566-2015 standard. (Used with permission from [9].)



**FIGURE 11.** (a) An ASD with AFE converter with dry-type isolation transformer. (b) An ASD with diode front-end converter with dry-type isolation transformer (note multiple secondary windings on the transformer in comparison to (a). (Source: TMEIC; used with permission.)

manufacturer. The availability of the transformer will depend on the power conversion topology that the manufacturer uses and how the ASD is packaged. Figure 11 shows a side-by-side comparison of two topologies of VSI drives that use a DIT. In Figure 11(a), the transformer swap-out for replace or repair would be faster, easier, and less labor intensive than for the ASD in Figure 11(b). This is due to more cables' involvement in the Figure 11(b) setup.

#### Future Improvements in Converter Technology

From their beginning as a simple six-pulse converter to today's most advanced converters, ASD isolation and converter techniques have come a long way in terms of power density, harmonic mitigation, overall foot-print, price, and capability. Diode-based converters and transformer isolation techniques are well understood and widely applied. With the introduction of low-loss IGBTs, reductions in price, and increased reliability, AFE technologies using IGBTs are also being applied at the 1,000–4,000-hp range, even for applications that do not need regeneration. Since IGBTs applied to these drives have a higher switching frequency (on the order of 2–5 kHz), they can mitigate all the low-order harmonics, providing for a net current THD of less than 2%.

#### Conclusions

While significant time and resources are spent evaluating the load-side performance of the ASD, including installation, specification, and post-installation support, very little effort is spent evaluating the line-side performance. Not all converter topologies are created equal, and proper selection depends on the power system available, requirements imposed by the utility provider, and overall installation requirements. Selecting the right kind of drive isolation technique is critical.

This article reviewed available converter topologies and drive isolating techniques, line-side effects, pros and cons, mitigation techniques, and selection criteria for each. The authors hope it can be used as a guide for making the correct selection and to improve the understanding of drive isolation techniques.

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#### References

[1] B. Lockley, "Adjustable speed drives in the petrochemical industry," in *Proc. 2002 IEEE Industry Applications Conf., 37th IAS Annu. Meeting*, Pittsburgh, PA, 2002, vol. 2, pp. 1240–1243.

[2] J. Gardell et al. (2008). "Adjustable speed drive motor protection applications and issues." IEEE Power and Energy Society Power System Relaying Committee. [Online]. http://www.pes-psrc.org/kb/published/ reports/Final\_J1\_ASD\_Motor\_Protection\_Application\_and\_Issues\_Working \_Group\_Report.pdf

[3] S. Kouro, J. Rodriguez, B. Wu, S. Bernet, and M. Perez, "Powering the future of industry: High-power adjustable speed drive topologies," *IEEE Ind. Appl. Mag.*, vol. 18, no. 4, pp. 26–39, July–Aug. 2012. doi: 10.1109/MIAS.2012.2192231.

[4] M. Verma, D. Phares, I. I. Grinbaum, and J. Nanney, "Cooling systems of large capacity adjustable speed drive systems," in *Industry Applications Society 60th Annu. Petroleum and Chemical Industry Conf.*, Chicago, 2013, pp. 1–11.

[5] D. A. Paice, *Power Electronic Converter Harmonics: Multipulse Methods for Clean Power*. Piscataway, NJ: IEEE Press, 1996.

[6] P. C. Sen, *Principles of Electric Machines and Power Electronics*. Hoboken, NJ: Wiley, 2014.

[7] IEEE Recommended Practices and Requirement for Harmonic Control in Electric Power Systems, IEEE Standard 519, 1992.

[8] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, IEEE Standard 519, 2014.

[9] IEEE Standard for Performance of Adjustable-Speed AC Drives Rated 375 kW and Larger, IEEE Standard 1566, 2015.

[10] M. Verma, N. Bhatia, S. Holdridge, and T. O'Neal, "Isolation techniques for various topologies of medium voltage adjustable speed drives," in *Proc. 2017 Petroleum and Chemical Industry Tech Conf.* (*PCIC*), Calgary, AB, Canada, pp. 327–344.