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Current source inverter vs. Voltage source inverter topology

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Abstract

In the medium voltage adjustable speed drive market, the various topologies have evolved with components, design, and reliability. The two major types of drives are known as voltage source inverter (VSI) and current source inverter (CSI). In industrial markets, the VSI design has proven to be more efficient, have higher reliability and faster dynamic response, and be capable of running motors without de-rating.

VSI fully integrated design saves money with higher efficiencies, minimizing install time, eliminating interconnect power cabling costs, and reducing building floor space. Efficiencies are 97% with high power factor through all load and speed ranges. Fast dynamic response for rapid changes in motor torque and speed allow a wide range of applications. Minimum component count increases the mean time to failure (MTTF), an important number in critical uptime applications. Also, new replacement motors are not required for retrofit applications. All of these factors produce a high-quality, robust, industrial design.

Introduction

Adjustable frequency drives (AFDs) are designed to allow full torque and speed control of the operating motor; how this is accomplished varies among manufacturers and the various design topologies. All medium voltage industrial AFDs consist of a converter section, a DC link, and an inverter section (see **Figure 1**).

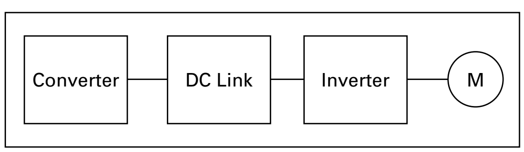

Figure 1.

The converter section converts utility/line AC voltage (50/60 Hz) to DC. The DC link transmits the DC voltage to the inverter, provides ride-through capability by storing energy, and provides some isolation from the utility/line.

The inverter converts the DC voltage and transmits a variable voltage or current and frequency to the motor. By independently changing the current and frequency, the drive can adjust the torque produced by the motor as well as the speed at which it operates, respectively.

There are more components typically required for a fully integrated system, which includes an input isolation, a transformer (or reactor), and an output filter (option), shown in **Figure 2**.

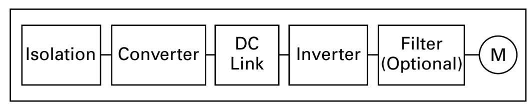

Figure 2.

Current source inverter

The way each of the drive building blocks operates defines the type of drive topology. The first topology that will be investigated is the current source inverter (CSI). The converter section uses silicon-controlled rectifiers (SCRs), gate commutated thyristors (GCTs), or symmetrical gate commutated thyristors (SGCTs). This converter is known as an active rectifier or active front end (AFE).

The DC link uses inductors to regulate current ripple and to store energy for the motor. The inverter section comprises gate turn-off thyristor (GTO) or symmetrical gate commutated thyristor (SGCT) semiconductor switches. These switches are turned on and off to create a pulse width modulated (PWM) output regulating the output frequency.

The design in **Figure 3** implements cascaded SGCT devices to achieve a 4160V system rating. A gate driver is required for each of the switching devices to control the device switch timing.

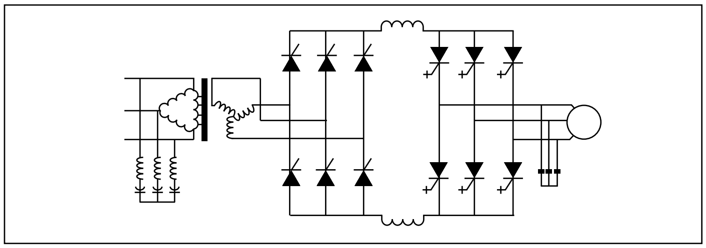

Figure 3. ①

The CSI design requires input and output filters due to high harmonic content. The input (**Figure 3**) is similar to a low voltage (LV) drive six-pulse input. At higher horsepower, a six-pulse active front end (AFE) input creates harmonics in the power system and poor power factor. To mitigate this issue, drive manufacturers combine either input transformers or reactors and harmonic filters to reduce the detrimental effects of the drive on the power system at the point of common coupling (PCC).

Voltage source inverter

The voltage source inverter topology uses a diode rectifier that converts utility/line AC voltage (60 Hz) to DC. The converter is not controlled through electronic firing like the CSI drive. The DC link is parallel capacitors, which regulate the DC bus voltage ripple and store energy for the system.

The inverter is composed of insulated gate bipolar transistor (IGBT) semiconductor switches. There are other alternatives to the IGBT: insulated gate commutated thyristors (IGCTs) and injection enhanced gate transistors (IEGTs). This paper will focus on the IGBT as it is used extensively in the MV VSI drives market. The IGBT switches create a PWM voltage output that regulates the voltage and frequency to the motor.

The design in **Figure 4** shows a neutral point clamped (NPC) three-level inverter topology. The IGBT switching devices are cascaded to achieve a 4160V system rating.

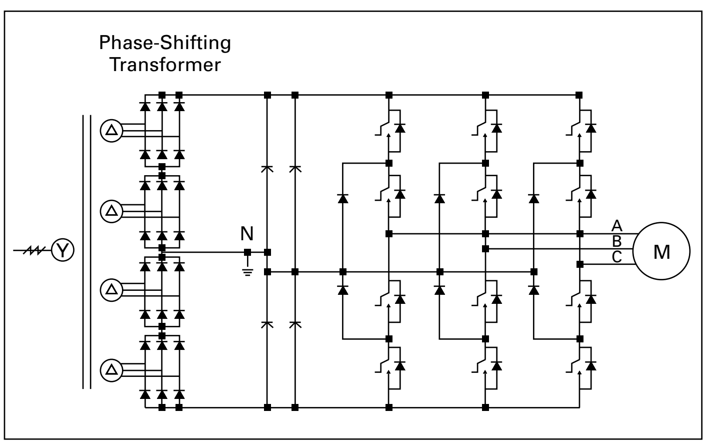

Figure 4.

Size consideration

Different drive topologies require many integrated components to work. The SC9000™ EP VSI drive is fully integrated, while many CSI drives are non-integrated. Fully integrated design incorporates all necessary components for a “cable-in, cable-out” installation.

In the following figures, the different integrated designs are illustrated. The dashed lines indicate components incorporated in a single assembly design.

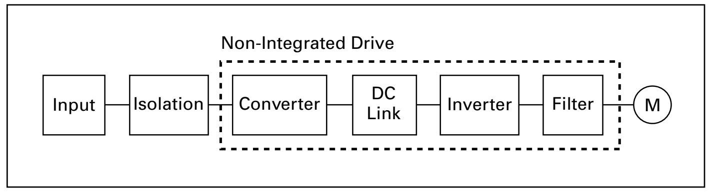

Figure 5.

Non-integrated designs require an external isolation means. In a CSI design, this would be a transformer or a harmonic filter/reactor. Poor power factor and harmonics generated by the CSI input require very large K-rated transformers or reactor/filter banks. Incorporating all these components within a single assembly significantly increases the footprint of the non-integrated drive. In high-horsepower applications, transformers or filters/reactors have to be placed outside of the control room.

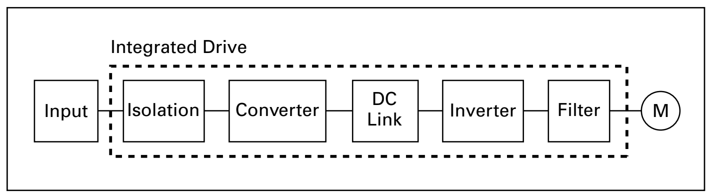

Figure 6.

An integrated design goes one step further and places the isolation within the drive assembly. However, an external contactor and an isolation switch or a breaker are required to feed the drive lineup.

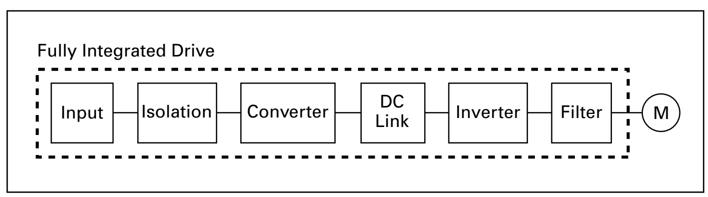

Figure 7.

The fully integrated design incorporates an input contactor, an isolation switch, protective fuses, and a phase-shifting isolation transformer in a complete drive assembly. The SC9000 EP VSI drive uses this approach in a very small footprint. By integrating all components into a single assembly, floor space can be reduced up to 65% over the traditional non-integrated design. **Table 1** shows the floor space required for a fully integrated 4160V, 1500 hp variable torque rated drive. ①

Table 1. Required Floor Space

	Inches (mm)		Square Footage					
Drive Design	Width	Depth	Area	Switch-gear	Trans-former	Addi-tional	Total	% Inc.
SC9000 EP, 24-pulse, VSI	95.00 (2413.0)	50.00 (1270.0)	33.0	—	—	0.0	33.0	—
6-pulse w/reactor, CSI	146.00 (3708.4)	40.00 (1016.0)	40.6	16.3	—	16.3	56.9	72%
PWM w/reactor, CSI	138.00 (3505.2)	40.00 (1016.0)	38.3	16.3	—	16.3	54.6	66%
18-pulse no reactor, CSI	122.00 (3098.8)	40.00 (1016.0)	33.9	16.3	22.6	38.9	72.8	121%
6-pulse no reactor, CSI	110.00 (2794.0)	40.00 (1016.0)	30.6	16.3	22.6	38.9	69.5	111%

The SC9000 EP saves significant space over other non-integrated CSI drive designs. The competition can be as much as 121% larger for the same horsepower drive.

Table 2 lists various output frequency and loading values for a 500 hp medium voltage applied to a test stand dynamometer. The efficiency values diverge significantly toward the lower frequency and load spectrum of the test.

Table 2. Drive and Motor System Efficiency

Frequency (Hz)	Load (%)	CSI AFE	SC9000 EP	Δ Efficiency
60	100	92	97.5	5.64%
50	60	85	97	12.37%
40	30	77	96.6	20.29%
30	12.5	65	96	32.29%

One of the best selling points of a drive is the ability to control motor speed. In a typical pump or fan application, pump and fan power curves can be applied to show the typical savings using a drive vs. a mechanical damping solution, where all excess power is lost through heating.

All drives save money for fan and pump loads, but not all drives save money equally.

Taking the numbers from the example above and using an average of $0.05 per kWh, the difference adds up quickly: more than $80,000 over five years.

Because all drives operate as power conversion devices, how can one drive be more efficient than another?

Semiconductor switching devices have losses during turn-on and turn-off times that result in inefficiencies. Presently, CSI designs use MV SCR, GTO, SGCT devices in the inverter and converter. A GTO is a thyristor (SCR) that can be turned on and off during conduction. Gating circuitry gives a small signal to turn on the device, and a large reverse signal to turn off the device. An SGCT is similar to a GTO but can block voltages in both directions, and the gate drive circuitry is built around the device rather than mounted separately. Modern VSI designs use MV IGBT devices and an external low power gate driver.

Table 3. SCR ②

Maximum Ratings	V_{DRM}	V_{RRM}	I_{TAVM}	I_{TRMS}	—
	12,000V	12,000V	1500A	2360A	—
Switching Characteristics	Turn-on time	Turn-off time	di_T / dt	dv_T / dt	Q_{rr}
	t_{gt} = 14 μs	t_q = 1200 μs	100A / μs	2000V / μs	7000 μC

Note: Part number: FT1500AU-240 (Mitsubishi)

Table 4. GTO ②

Maximum Ratings	V_{DRM}	V_{RRM}	I_{TGQM}	I_{TAVM}	I_{TRMS}	—
	4500V	17V	4000A	1000A	1570A	—
Switching Characteristics	Turn-on switching	Turn-off switching	di_T / dt	dv_T / dt	dv_{G1} / dt	dv_{G2} / dt
	t_d = 2.5 μs	t_s = 25.0 μs	500A / μs	1000V / μs	40A / μs	40A / μs
	t_r = 5.0 μs	t_f = 5.0 μs	—	—	—	—
On-State Voltage	$V_{T(on\text{-}state)}$ = 4.4V at I_T = 4000A					

Note: Part number: 5SGA 40L4501 (ABB)

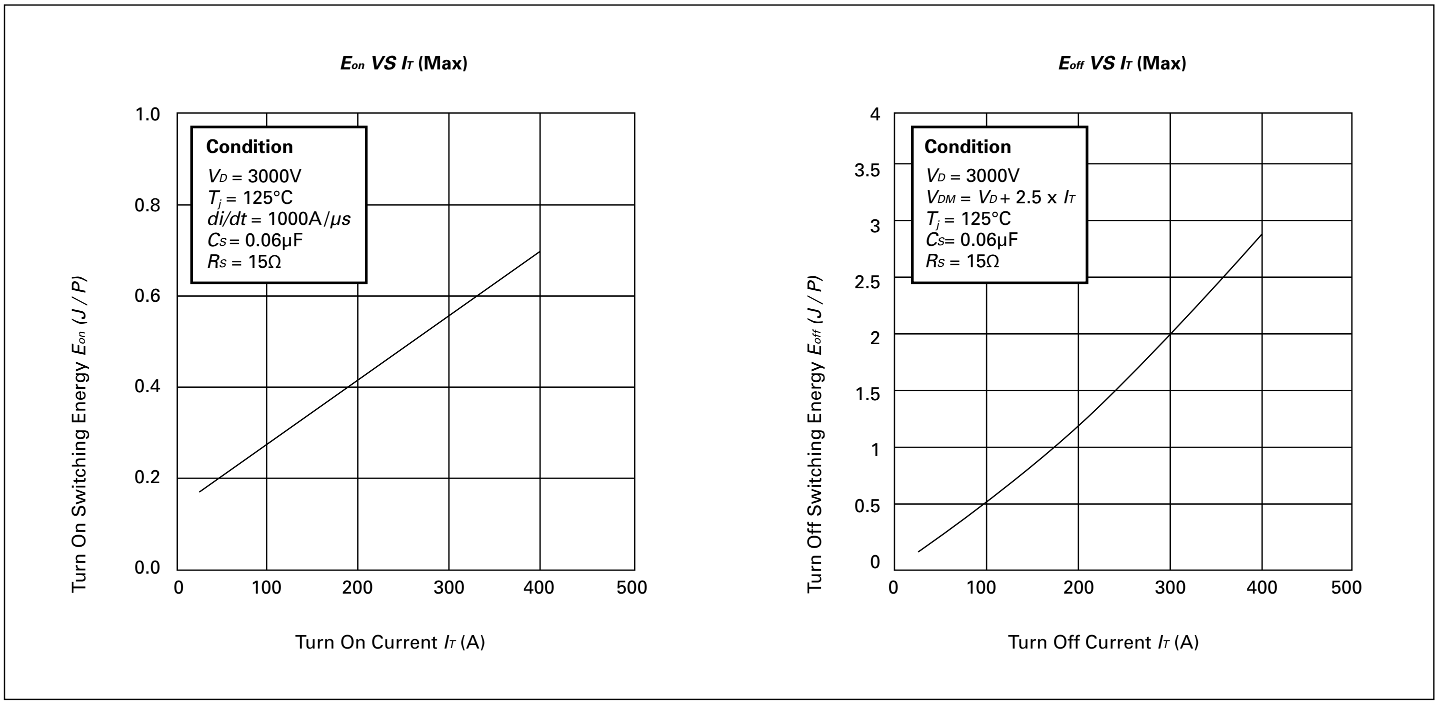

Figure 8. SGCT Switching Losses ③

Switching and on-state conduction losses are calculated below from **Table 3**, **Table 4**, and **Figure 8**. Values from the data sheets are acquired from a full power test and are linearly interpolated to simplify calculations. Turn-on and off power that is not specifically stated is approximated:

$$P_{loss,\ avg} = \frac{V_d I_o f_s\ (t_d)}{2}$$

Equation 1. General Switching Loss Formula ④

$$P_{loss,\ sw} = 1.64 \times 10^{-3} \times P_{output}$$

Equation 2. SCR Switching Loss

The SCR switching power loss is linearly interpolated because it is a function of current and voltage. Switching frequency is fixed at 120 Hz. The turn-off switching energy includes the reverse recover charge.

$$P_{loss,\ sw} = 9.6 \times 10^{-4} \times P_{output}$$

Equation 3. GTO Switching Loss

GTO switching power loss is also linearly interpolated. The t_r (rise time) and t_f (fall time) values are the major contributions to switching loss. The switching frequency is fixed at 240 Hz.

$$E_{on} = 1.35 \times 10^{-3} \times I_{on\text{-}state} + 0.15$$

$$E_{off} = 7.67 \times 10^{-3} \times I_{on\text{-}state} - 0.2$$

Equation 4. SGCT Switching Loss

$$P_{sw,\ loss} = f_{fund} \times N \times E_{sw}$$

$$P_{cond,\ loss} = V_{tm} \times I_t$$

$$P_{loss} = P_{sw,\ loss} + P_{cond,\ loss}$$

Equation 5. SGCT Switching and Conduction Loss ⑤

The pulse numbers (N) can vary based on the fundamental frequency (f_{freq}) with selective harmonic elimination (SHE) switching technique. N=11 at 30 Hz is fundamental; however, the maximum switching frequency is 540 Hz and N=9 is used at 60 Hz. The total power loss includes the on-state conduction losses calculated from data sheet values and average current.

$$\eta = \frac{P_{out} \times 100}{P_{out} + P_{loss}}$$

$$\eta_{total} = \eta_{isolation} + \eta_{drive} + \eta_{filter}$$

Equation 6.

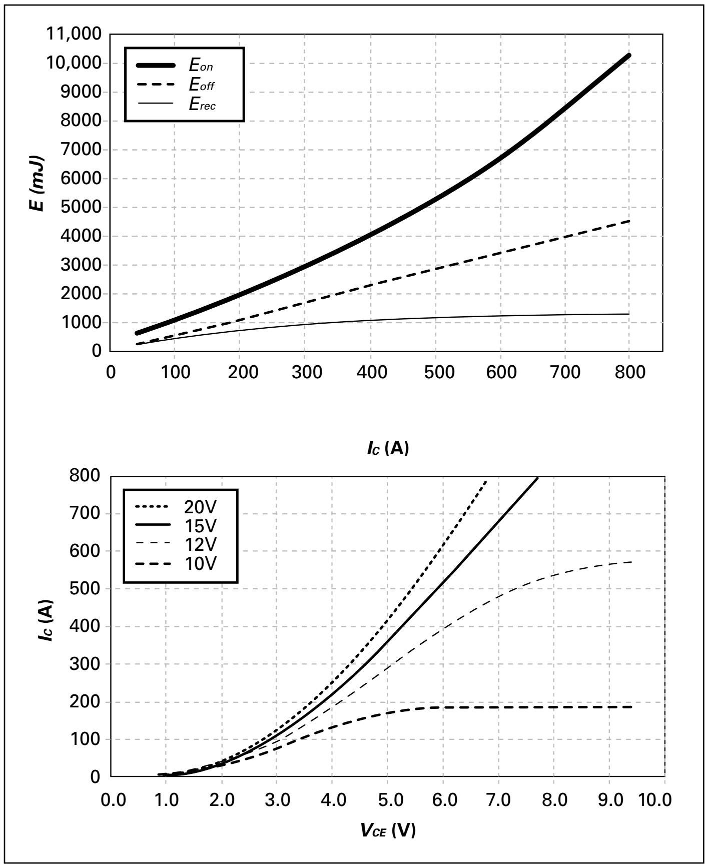

Figure 9. IGBT Switching and Conduction Losses [6]

The IGBT is a high-efficiency device with faster turn-on and off times. The energy and power loss of each IGBT is calculated:

$$E_{on}\ (J / P) = 10 \times 10^{-3} \times I_{on\text{-}state}$$

$$E_{off}\ (J / P) = 5.75 \times 10^{-3} \times I_{on\text{-}state} - 0.025$$

Equation 7. IGBT Switching Loss

$$P_{sw,\ loss} = f_{sw} \times (E_{on} + E_{off})$$

$$P_{cond,\ loss} = V_{tm} \times I_c = 329W$$

Equation 8.

Total inverter and AFE converter power loss is calculated with only half of all switching devices on at the same time. In most switching techniques, such as space vector modulation, half the devices are on in any instant. Diode bridge efficiency is included in the VSI system efficiency calculation. The total drive efficiency is calculated with an assumed 99% efficient transformer for VSI and filter/reactors for the CSI topology (**Table 5**).

Table 5. Drive Efficiency

Device	1500 hp (p.u.)	Topology	Efficiency
IGBT	1	24-pulse NPC VSI	97.7%
	0.125	24-pulse NPC VSI	97.8%
SGCT	1	CSI	95.7%
	0.125	CSI	95.9%
GTO + SGCT	1	CSI	95.9%
	0.125	CSI	93.4%
SCR + SGCT	1	CSI	95.86%
	0.125	CSI	89.56%

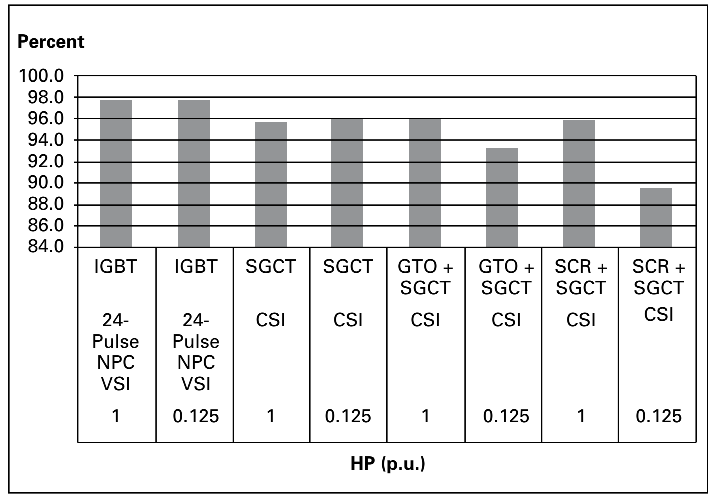

Figure 10. Drive Efficiency

From the calculations, each topology is analyzed for the overall drive efficiency. The highest-efficiency design is the VSI design, using IGBT devices. The SGCT devices are efficient; however, the slower switching speeds and higher on-state conduction add up in the CSI design. The lowest-efficiency device is the SCR.

Reliability

Failure-in-time (FIT) is a well known and frequently used industry reliability tool to calculate collectively the MTTF of equipment with multiple components. Calculations typically include major components that are critical to system operation. In the example that follows, the power components and semiconductor devices are evaluated using numbers based on industry-known failure rates. [7]

Table 6. VSI NPC Topology [8]

Component	Quantity	FIT	Total FIT
Diodes	30	100	3000
DC capacitors	4	300	1200
IGBT	12	400	4800
Gate driver	12	100	1200
Total	—	—	10,200

Table 7. CSI SGCT AFE Topology [9]

Component	Quantity	FIT	Total FIT
SGCT	24	200	4800
Filter capacitors	6	300	1800
Gate driver	24	2915	69,960
Total	—	—	76,560

$$MTTF = \frac{1}{\lambda} = \frac{1}{10{,}200} * 10^9\ hours = 98{,}039\ hrs$$

$$MTTF = 11.2\ yrs$$

Equation 9. VSI NPC Topology

$$MTTF = \frac{1}{\lambda} = \frac{1}{76{,}560} * 10^9\ hours = 13{,}062\ hrs$$

$$MTTF = 1.5\ yrs$$

Equation 10. CSI Topology

While all semiconductor components have similar failure rates, the significant difference is the number of components and the gate driver circuitry for each device. The higher failure rate of the SGCT gate driver is from the use of electrolytic capacitors, designed to deliver the required very high peak turn-off energy. From the SGCT data sheet, the peak forward and reverse gate current requirements are 250A and 400A, respectively. The IGBT requires only ±15V logic level control and milliamp current requirements to turn on and off. This significantly reduces the complexity and design of the gate board driver, eliminating the need for many large electrolytic capacitors. The calculations show that VSI drives have a much higher MTTF than CSI drives.

Dynamic response

Dynamic response is defined as the reaction time of the system when a step change in reference occurs. High dynamic response times are crucial in precise and high-performance applications. High dynamic response is limited by the ability of the system to control the current or torque of the motor.

The CSI design incorporates two large DC inductors for:

- Current ripple minimization
- Energy storage
- Fault current limiting

Inductors with values of 0.5 to 1.0 per unit (p.u.) are not uncommon in the CSI design. Because time rate of change for current flow is proportional to the inductor size (H), the dynamic performance decreases. Current ripple within the inductor is inversely proportional to the inductor size. It is a significant trade-off between response time and current ripple. The inductor is also sized to reduce short-circuit fault current levels and rise time to allow the SGCT devices to turn off safely.

VSI designs do not use any DC inductors within the DC link. The capacitors provide the instantaneous current required in dynamic systems, and therefore are better suited for high-performance applications.

Input power quality

At lower end speeds and loads, CSI GTO and SCR designs have poor input power factor and harmonics. As the AFE regulates input current, firing angle (alpha) changes. The firing angle at full power is typically 20 degrees. This delayed firing angle creates a large displacement power factor (DPF) as seen in **Figure 11**. Given a constant current due to the large DC link inductors, the current is seen as a square wave (poor harmonics). To mitigate poor power factor and harmonics, multi-pulse phase shifting transformers are used on the input to the drive. Many CSI drives use a 12-pulse or 18-pulse option; however, this may not meet certain harmonic standards such as those stated in IEEE® 519. SCR/GTO input drives have the worst power factor and harmonics, and require very large K-rated transformers to mitigate harmonics.

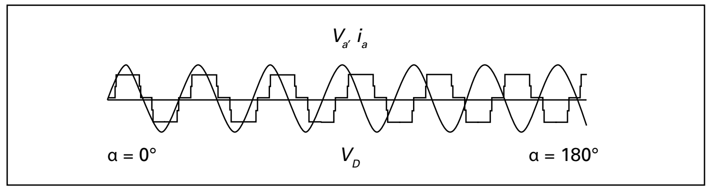

Figure 11.

The SGCT AFE design uses PWM switching to regulate the current. The PWM AFE has a higher switching frequency than the SCR example given above. With conventional PWM switching, the AFE produces higher lower harmonic content. These harmonics are detrimental to power systems and do not meet certain harmonic limitations such as those outlined in IEEE 519. To remove these lower order current harmonics, a special modulation technique is used (selective harmonic elimination, or SHE) to eliminate the 5th, 7th, and 11th harmonics. Higher order harmonics are mitigated using filters. The filters must be tuned properly to each drive, and resonance can occur with the power system if not done correctly. If a filter capacitor fails, a sensitive power system can be compromised. If capacity and loads are added to the system, the filter may need to be adjusted. ②

The SC9000 EP VSI design uses a 24-pulse phase shifting transformer. The 24-pulse design meets IEEE 519 requirements in all systems. There are no filters to tune to a particular power system, and, as the power system grows and loads and capacity are added, there is no hazard of resonance. Each transformer is designed specifically for the maximum load of the drive; running at a lower power does not alter performance. In **Figure 12**, the voltage THD is less than 1.2% and the current THD is less than 5%, meeting the IEEE 519 requirements on the tested system.

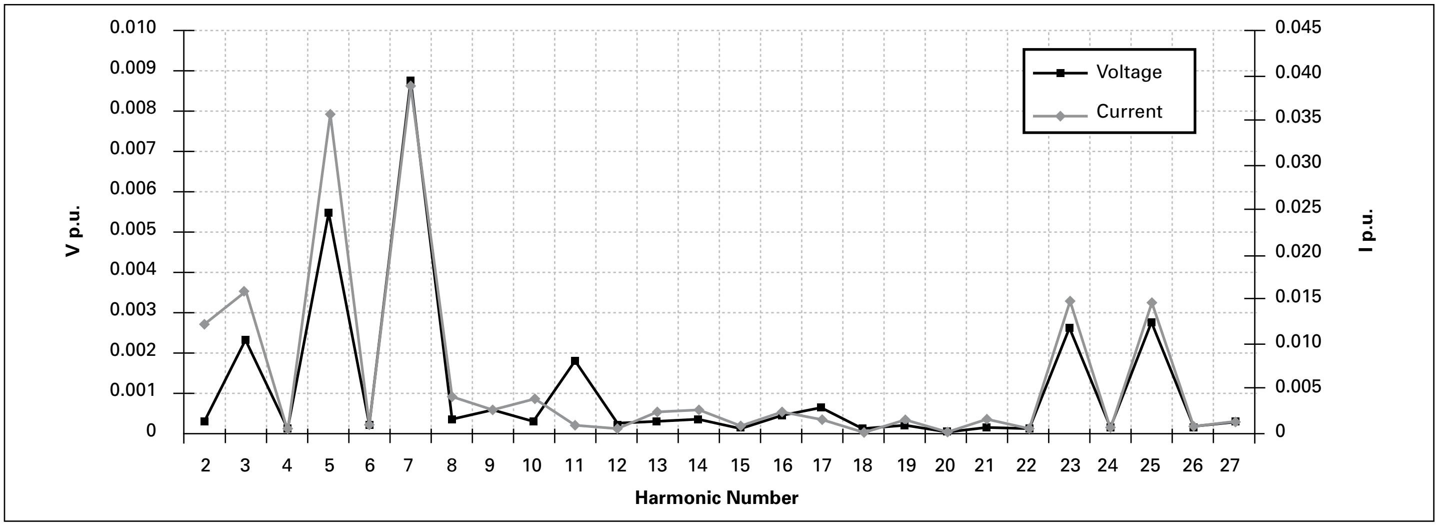

Figure 12. Input Harmonics

Motor requirements

With the proliferation of drive systems on motors, different phenomena have been observed with detrimental effect. The two major observations with drives are:

- Neutral point shift / common mode voltage
- Torque pulsations / cogging

Common mode voltage on a motor when applied with a drive is when both conductors experience the same or common voltage level. This can happen when the input voltage on a system is on an ungrounded wye or delta secondary. The voltage input can drift, and neutral is no longer referenced at zero. This results in a higher line to neutral voltage stress on the winding insulation within the motor.

The CSI design transfers common mode voltage to the motor from the lack of isolation transformer or common mode choke. On the GTO, SCR, or SGCT design, the motor is susceptible to common mode because there is no hard reference ground in the inverter design. Without mitigation, winding insulation breaks down and can cause premature failure on the motor.

The SC9000 EP VSI design incorporates a phase-shifting isolation transformer as well as a neutral point clamped inverter design. The isolation transformer and hard-grounded neutral point eliminate the common mode voltage at the motor. This allows the VSI drive to operate on a standard motor and doesn't require special voltage insulation ratings.

Torque pulsations or cogging is common with the CSI design. Torque pulsations are the result of a high harmonic content in the output current of the drive. Torque pulsations result in stress to motor shafts and pumps, fans, conveyer (belts), or any ultimate driven load.

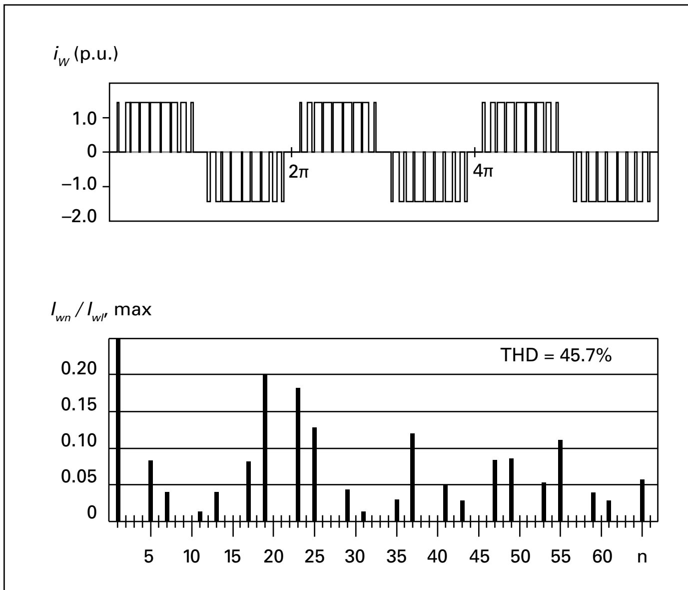

Figure 13. ②

The torque pulsations occur from harmonic current pulses. For example, the 5th harmonic contributes to negative sequence (opposite rotation) torque pulsations, and the 7th harmonic to positive rotation pulse. **Figure 13** shows the raw current output waveform with no filter and the harmonic spectrum; THD is measured at 45%. Filters are required, and, if failure occurs, damage to the motor and driven load will occur. The required output filter results in lost efficiency and loss of voltage, and limits the torque response. ①

CSI drives require a closed-loop control (field-oriented control) and cannot operate in an open-loop mode (output will become unstable). This limits multi-motor applications, since motor parameters are necessary for proper closed-loop control. V/Hz control (open-loop) is widely used in VSI drive applications, where different rating motors can be run on the same drive. Another limiting factor is that the CSI output filter must be tuned for a particular motor; different motor leakage inductances can create unstable and resonant conditions with the capacitive output filter and switching frequency. ⑩

The VSI current output has very low current harmonics and does not require a filter. The three-level output increases switching steps to create low harmonic content. In **Figure 14**, the top portion is the line-to-line voltage, and the lower portion is the phase current. Current harmonic level in the figure is less than 11%. The SC9000 EP can run in V/Hz or vector control.

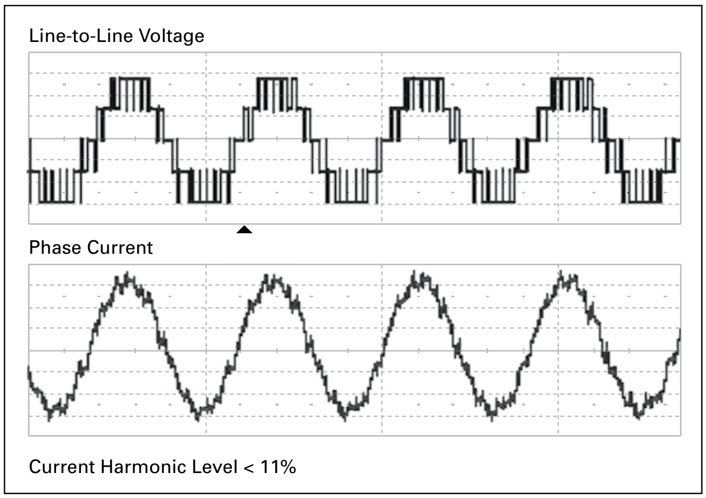

Figure 14. VSI Output

Conclusion

Many key points were discussed about the major differences between the voltage source inverter and the current source inverter drive topologies. From size, efficiency, components, and motor compatibility, the VSI design has been proven in countless industrial applications and met with success.

Table 8. Topology Comparison

	CSI	VSI
Size		
Non-integrated	Standard	—
Integrated	Option	—
Fully integrated	Limited	Standard, smallest footprint
Efficiency		
Full power	95.7%	97.7%
Lower power	89.9%	97.8%
Reliability		
Components	Low, high component count	High, low component count
MTTF	1.5 years	11.2 years
Dynamic Response	Limited by DC choke, filter	Fast, no limiting reactors
Input Power		
Harmonics	High, requires isolation / filter	Low, meets IEEE 519
Power factor	Low, requires PWM or multipulse transformer	High, standard 24-pulse transformer
Resonance issue	Must tune input filter	No
Motor Issues		
Filter	Requires filter, causes cogging without, resonance	No, standard motor compatible
Common mode	Yes, requires isolation and common mode choke	No, isolation transformer and neutral point clamp eliminates
Multi-motor	No, single motor	Yes, rated motor and below

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