

Harmonic Mitigation in Variable Frequency Drives

6-Pulse Drive with Passive Filter vs. 18-Pulse Drive

Retain for future use.

Introduction

The proliferation of variable frequency drives (VFDs) has brought increased attention to harmonic effects created by drives. A standard 6-pulse drive with no harmonic mitigation may interfere with neighboring equipment, reduce equipment life, and negatively impact the utility power quality. Under some circumstances, the total harmonic current distortion (THD_i) may approach the level of the fundamental current.

Schneider Electric offers a low harmonic, 18-pulse drive (Clean Power Drive) to mitigate the effects of current harmonic distortion and now offers an alternative solution—the use of a traditional 6-pulse drive equipped with a passive harmonic filter (PHF). This data bulletin compares the performance of a 100 hp 18-pulse drive with the performance of a standard 100 hp 6-pulse drive equipped with a passive harmonic filter.

6-Pulse Overview

Figure 1 shows a basic block diagram for a variable frequency drive. Three-phase power is applied to the converter. The converter transforms the three-phase power into DC power. Then the DC is applied to the inverter, which transforms the DC into variable fundamental frequency pulse width modulated AC power that powers the motor.

Figure 1: Basic VSD Block Diagram

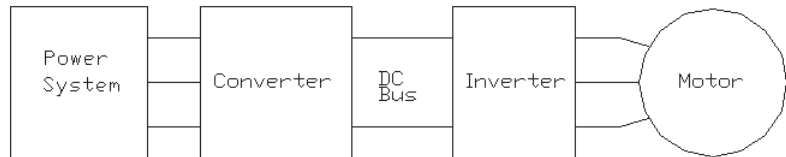


Figure 2 (page 2) shows a block diagram for a 6-pulse power system and converter. The power system is typically a wye connected transformer secondary. The wye connection has three voltages that are 120° out of phase, and the converter has six rectifiers. The theoretical input current harmonics for rectifier circuits are a function of pulse number [1]:

Equation 1: $h = (np \pm 1)$
 where $n = 1, 2, 3,$ and so on
 and $p =$ pulse number

The lowest theoretical harmonic for a 6-pulse converter is the fifth.

Figure 2: 6-Pulse Power System and Converter

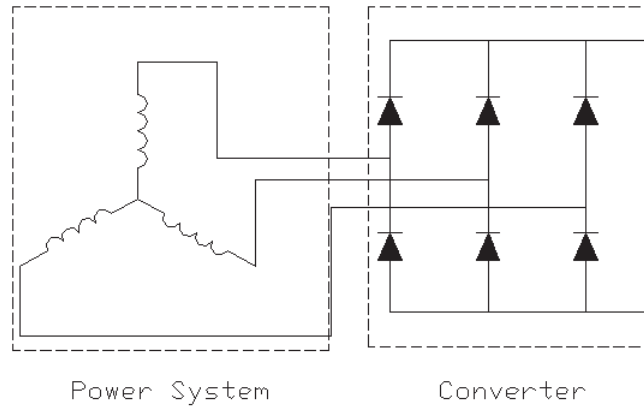
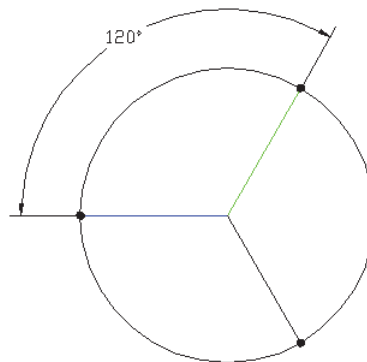


Figure 3 shows a vector representation of the three-phase power system voltage. When the power system provides balanced three-phase power, the 6-pulse converter performs close to the theoretical harmonic performance. The three phases on the secondary of the typical delta-wye transformer provide balanced power to the converter.

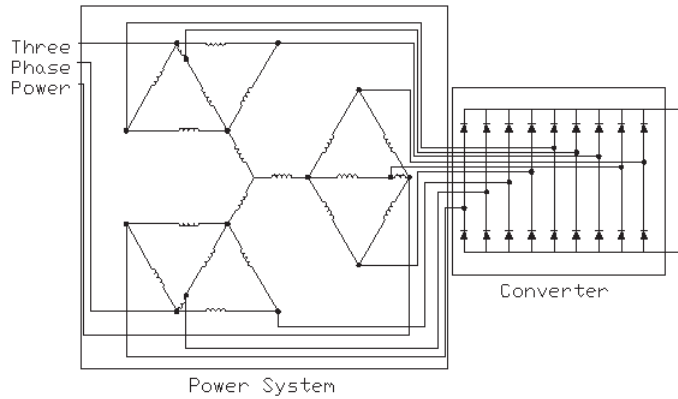
Figure 3: Three-Phase Power System Voltage Vector Representation



18-Pulse Overview

Figure 4 shows a nine-phase power system and an 18-pulse converter. The power system is a patented autotransformer [2] that has an output of nine phases that are each 40° out of phase with the other. There are eighteen rectifiers in the converter. Applying Equation 1 (see page 1), the input current would only have harmonic components at the following multiples of the fundamental frequency: 17, 19, 35, 37, 53, 55, and so on, with a balanced system.

Figure 4: Nine-Phase Power System and 18-Pulse Converter



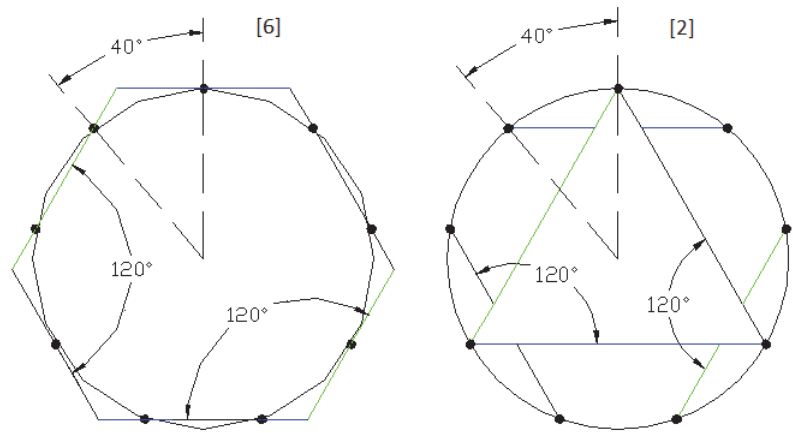
Note that the 5th, 7th, 11th, and 13th harmonics are theoretically absent in an 18-pulse converter. Since the magnitude of each harmonic is proportional to the reciprocal of the harmonic number, the 18-pulse system has theoretically low harmonic current distortion due to the inherently inductive nature of the power system.

Figure 5 (page 4) shows two patented vector representations of methods used to form a nine-phase power system [2] [6]. The three phases are represented by the blue, black, and green lines. A nine-phase power system has to be constructed from the available three-phase voltages on a transformer. All of the voltage vectors that evenly intersect the circle on the vector representation must be 120° out of phase with the others since they originate from a conventional three-phase system.

This is done with a transformer or autotransformer by using multiple windings from different legs of the three-phase core.

The leakage inductance between transformer windings also needs to be balanced to control voltage regulation. Theoretically, there are an infinite number of winding configurations possible to create the nine phases required for an 18-pulse system.

Figure 5: 18-Pulse Vector Representations of Transformer Windings



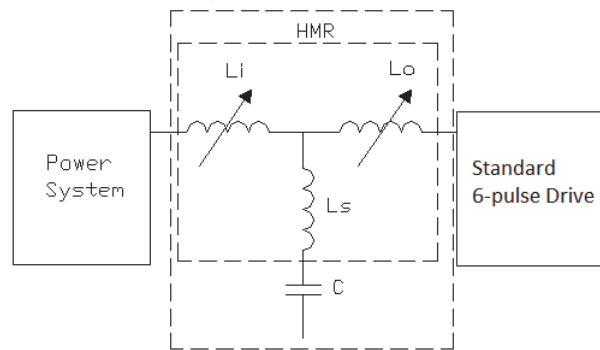
An 18-pulse system provides harmonic mitigation by cancelling harmonic currents at the 5th, 7th, 9th, and 11th harmonic order. Effective cancellation requires a balanced three-phase input system. Therefore any harmonic voltage distortion or imbalance of system voltages in either magnitude or phasing is not mitigated. Additional input impedance (inductance) is often added in series with the 18-pulse transformer to ensure a higher degree of system balance.

The system used for testing includes an 8% impedance reactor, nine-phase transformer, and diode bridge (behind the transformer). Many manufacturers of 18-pulse systems have included passive filtering to improve the performance issues due to construction or system imbalances. The most basic method is using an 8%–10% line reactor on the line side of the transformer.

Passive Harmonic Filter Overview

Figure 6 shows a single-phase schematic of a passive harmonic filter with a 6-pulse drive. Typically referred to as a *band rejection filter* or *notch filter*, it consists of an inductor and capacitor network. The passive harmonic filter is used between a standard three-phase power system and 6-pulse drive.

Figure 6: Passive Harmonic Filter Diagram



L_s and C are tuned to near the dominant 5th harmonic generated by 6-pulse drives. L_i prevents the filter from importing the 5th harmonic from other sources and overloading the filter. The series combination of L_i , L_s , and C

set the tuning frequency to the power system well below the 5th harmonic. Lo reduces the voltage boost due to the capacitors. Both Li and Lo also reduce the THD_i by adding wide band line filtering impedance.

Note that inductors Li and Lo are designed to operate in the saturation region at full load, resulting in variation in effective impedance. At reduced load, the effective impedance is higher, improving THD_i performance across all loading conditions.

Power Loss Comparison

Figure 7 shows a typical 18-pulse power circuit. Twelve additional rectifiers and a nine-phase transformer are added to the DC bus. The manufacturers of these systems publish both their 6-pulse drive power losses and the 18-pulse drive power losses. In order to calculate the power loss of just the added 18-pulse components, the losses of published standard 6-pulse drive product configurations were subtracted from the published power loss of the 18-pulse configuration. This was done to formulate a direct comparison to the typical losses of an equivalent passive harmonic filter. Table 1 (page 1) and Figure 8 (page 8) show the comparison of the 18-pulse added component losses to that of a passive harmonic filter. The data shows that losses from the passive harmonic filter are 34% –74% less than those from added 18-pulse components.

Figure 7: 6-Pulse Drive Conversion to 18-Pulse

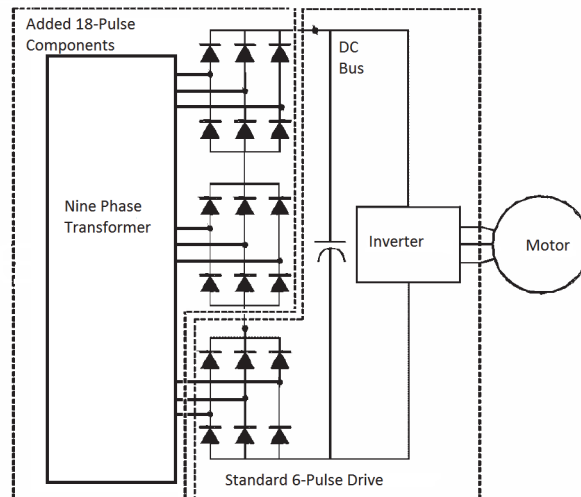


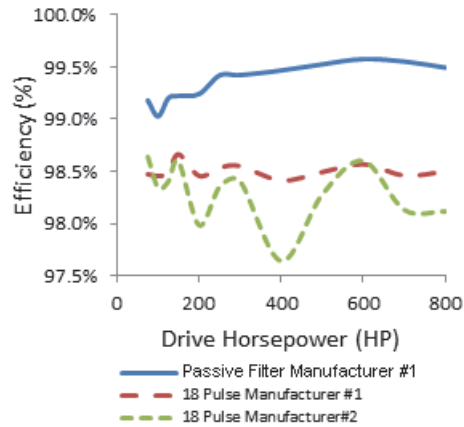
Table 1: Power Loss Comparisons

Drive HP	PHF	Additional Drive Components Manufacturer #1		Additional Drive Components Manufacturer #2	
	Power Loss (W)	Power Loss (W)	PHF Loss Reduction	Power Loss (W)	PHF Loss Reduction
75	702	1,307	46%	1,165	40%
100	1,035	1,641	37%	1,761	41%
125	1,096	2,076	47%	2,190	50%
150	1,343	2,309	42%	2,430	45%
200	1,514	3,078	51%	4,020	62%
250	1,543	3,900	60%	4,383	65%

Table 1: Power Loss Comparisons (continued)

Drive HP	PHF	Additional Drive Components Manufacturer #1		Additional Drive Components Manufacturer #2	
	Power Loss (W)	Power Loss (W)	PHF Loss Reduction	Power Loss (W)	PHF Loss Reduction
300	1,932	4,852	60%	5,350	64%
400	2,137	6,359	66%	9,450	77%
500	2,509	7,966	69%	9,101	72%
600	2,771	9,346	70%	9,143	70%
700	3,163	10,875	71%	13,200	76%
800	4,206	12,484	66%	15,650	73%

Figure 8: Power Loss Comparison



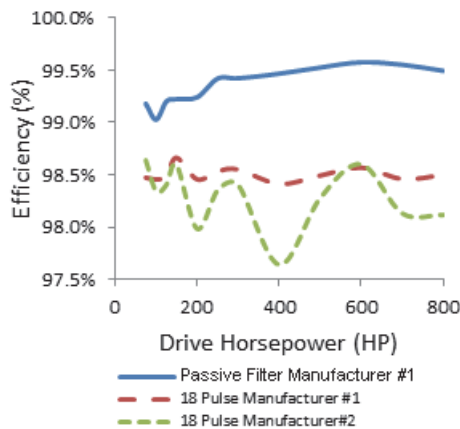
Efficiency Comparison

The percent filter efficiency is calculated using the following equation since both harmonic mitigation techniques have near unity power factor at full load:

$$\text{Equation 2: } \% \text{Efficiency} = \frac{P_{out}}{P_m} \times 100 = \frac{(V_{in} \times I_m \times \sqrt{3}) - P_{filter}}{(V_{in} \times I_m \times \sqrt{3})} \times 100$$

Figure 9 shows a comparison of the additional component losses of 18-pulse product lines of two manufacturers (see Table 1 on page 5) to the passive harmonic filter efficiencies. The passive harmonic filter typically is greater than 99% efficient, whereas the typical 18-pulse solution is about 98% efficient. In all cases the passive harmonic filter is more efficient than the 18-pulse drive added components.

Figure 9: Percent Efficiency of the Added 18-Pulse Components and Passive Harmonic Filter



THD_i Performance Comparison

The total harmonic current distortion (THD_i) performance of a typical 100 hp, 18-pulse drive and a 6-pulse drive with a passive harmonic filter was compared. Figure 10 compares the actual test data between an 18-pulse drive and a passive harmonic filter. The total harmonic voltage distortion (THD_v) was about 1.5% for most of the test conditions. In both cases, the 18-pulse and passive harmonic filter solutions meet requirements of <5% TDD_i (Total Demand Current Distortion) per IEEE 519.

Figure 10: Passive Harmonic Filter with 6-Pulse and 18-Pulse THD_i Versus Load

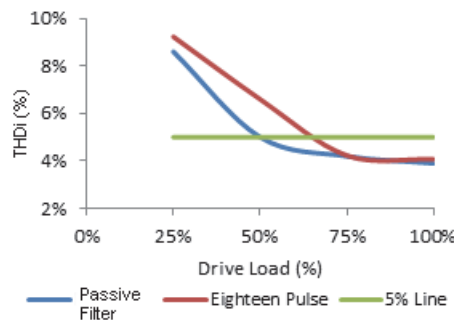
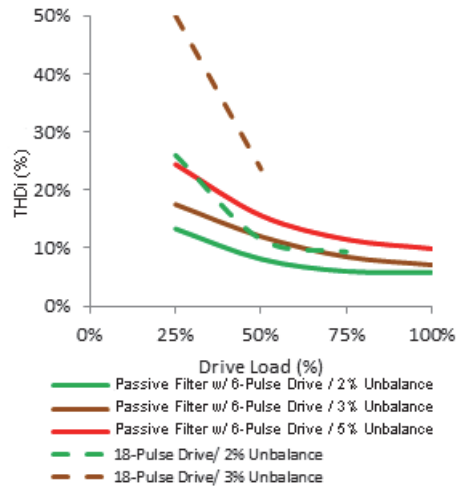


Figure 11 shows the harmonic mitigation performance of a standard 6-pulse drive with a passive harmonic filter as compared to an 18-pulse drive with a system voltage imbalance. The specification for the 18-pulse drive allowed for a maximum 3% voltage imbalance and tripped, so additional data was not taken. At reduce load the THDi for the 18-pulse system was considerably more pronounced than the standard 6-pulse drive with a passive harmonic filter. The 18-pulse drive had 50% THDi compared to 17.5% THDi for the standard 6-pulse drive with a passive harmonic filter at 25% load.

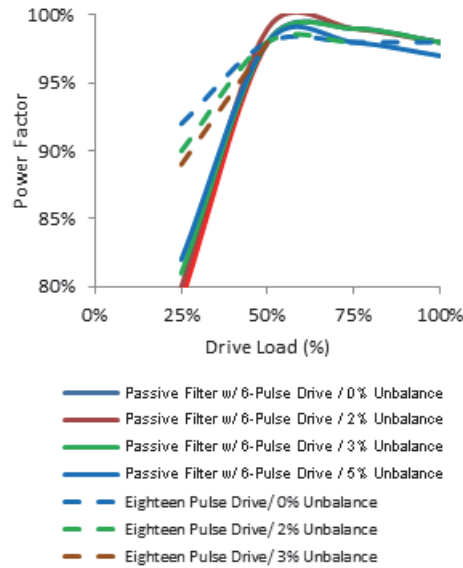
Figure 11: Passive Harmonic Filter with 6-Pulse Drive and 18-Pulse Drive THDi with System Voltage Imbalance



Power Factor Performance Comparison

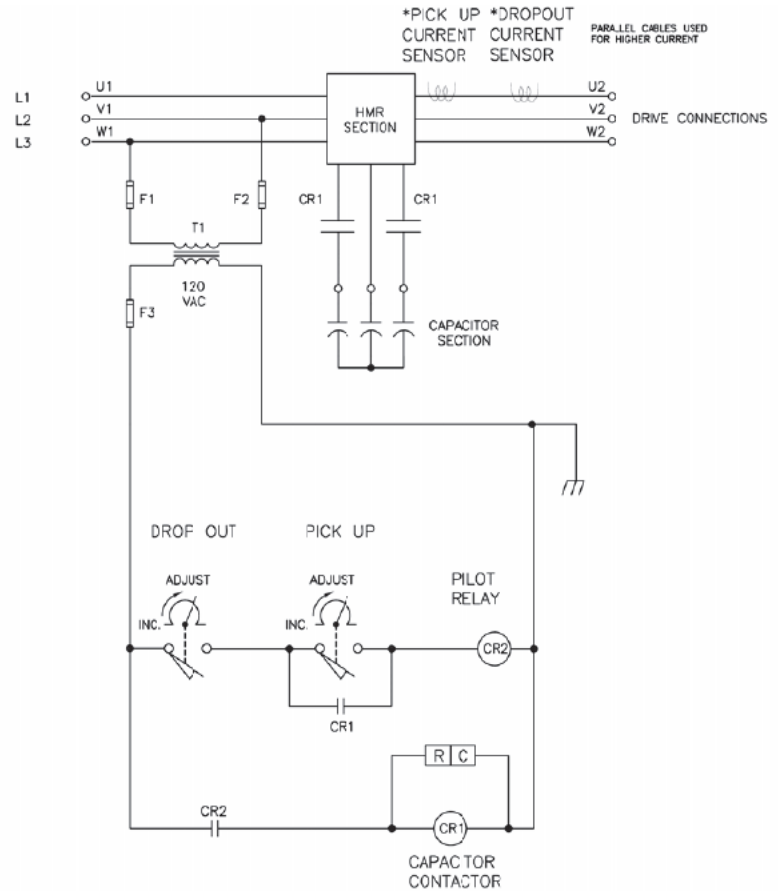
The power factor performance of a typical 100 hp 18-pulse drive and a 6-pulse drive with a passive harmonic filter was compared. Figure 12 shows the actual test data for comparison. Both harmonic mitigation techniques performed better than 98% power factor at loads greater than about 50%. The passive harmonic filter had a higher leading power factor at 25% load. The 18-pulse solution had a power factor of 92% compared to the 79% power factor at 25% load and no voltage imbalance.

Figure 12: Power Factor Versus Load



The reduced power factor at reduced loads for the passive harmonic filter is due to the capacitance. In many power systems, this leading power factor increases the efficiency of the system because it offsets some of the inductive loads that have a lagging power factor. In other systems, it can be problematic. Schneider Electric Services can help you evaluate your specific power system and operating mode to determine potential benefits and risks of operating at or near unity power factor.

Figure 13: Passive Filter Capacitor Disconnect Schematic



Size Comparison

Figure 14 shows a side-by-side comparison of the 100 hp 18-pulse transformer, reactor, and bridge as compared to the 100 hp filter harmonic mitigating reactor (HMR) and capacitors. The overall dimensions for each of the magnetic components are shown in Table 2. The 18-pulse transformer is about 80% larger than the inductor portion of the passive harmonic filter (PHF) and is considerably heavier.

Figure 14: 100 HP 18-Pulse Transformer

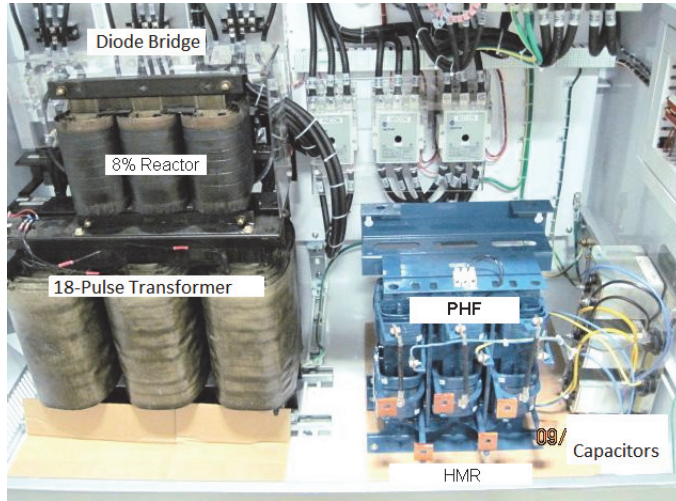


Table 2: 100 HP Magnetics Size Comparisons

	18-Pulse Transformer/Reactor	Harmonic Filter Magnetics
Height (in.)	28	15.25
Width (in.)	19	20
Depth (in.)	12	11.7
Volume (in ³)	6384	3569

Conclusion

Power quality issues are a growing concern for utilities and consumers of electrical equipment. The application flexibility of IEEE 519 allows consumers to consider alternate Points of Common Coupling (PCC) for addressing power quality concerns.

As a global expert in energy management, Schneider Electric has combined its experience in electrical distribution with drives and automation to provide innovative power quality solutions. Our flexibility allows us to address customer expectations using a wide range of harmonic mitigation solutions. Our solutions range from aggressive abatement at the point of offending equipment (drive terminals) using multi-pulse and passive filters, to drive solutions offering low harmonic signatures.

References

- [1] Hink, Karl "18-Pulse Drives and Voltage Unbalance." MTE Corporation.
- [2] Paice, Derek A. "Optimized 18-pulse type AC/DC, or DC/AC, converter system." US Patent 5,124,904. 23 June 1992.
- [3] Paice, Derek A. "Wye Connected 3-Phase to 9-Phase Auto-transformer with Reduced Winding Currents." US Patent 6,191,968. 20 February 2001.
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- [5] Shudarek, Todd A., Walcott, Wayne and Ruther, Wesley. "Harmonic Mitigation Devices and Applications Thereof." WIPO Patent Application WO/2012/103152.
- [6] Zhou, Dongsheng, Skibinski, Gary and Guskov, Nickolay N. "Nine-phase transformer." US Patent 6,335,872. 1 January 2002.