# Harmonic Mitigation in Variable Frequency Drives: 6-Pulse Drive with MTE Matrix AP Harmonic Filter vs. 18-Pulse Drive

November 13, 2012

Todd Shudarek, Principal Engineer

**MTE Corporation**
N83 W13330 Leon Road
Menomonee Falls WI 53051
www.mtecorp.com

**Abstract**

The proliferation of variable frequency drives (VFDs) has brought increased attention to harmonic effects created by drives. A standard 6-pulse drive without any harmonic mitigation technology may interfere with neighboring equipment, reduce equipment life, and negatively impact the utility power quality. Under some circumstances the total harmonic current distortion (THID) may approach the level of the fundamental current. Drive manufacturers offer a low harmonic, 18-pulse drive to combat these effects. An alternative solution is the use of a traditional 6-pulse drive equipped with a passive harmonic filter; however, typical passive harmonic filters experience reduced effectiveness at loads less than 100%. With the introduction of adaptive passive technology, the Matrix AP harmonic filter maintains strong harmonic filtering performance across a wide range of loads. This paper compares the performance of a 100 HP 18-pulse drive with the performance of a standard 100 HP 6-pulse drive equipped with a 128 amp Matrix AP harmonic filter.

The 6-Pulse drive with Matrix AP harmonic filter outperformed the 18-pulse drive in the following important areas:

- **Power loss:** Approximately 665 less watts consumed.
- **Overall efficiency:** 0.5% more efficient (99.0% vs. 98.5%).
- **Harmonic performance under balanced line conditions:** 1-2% better THID performance for loads 25-75% and equal performance for loads greater than 75%.
- **Harmonic performance under line imbalance conditions:** Significantly better performance. For example under 3% line imbalance, performance was 32.5% better (17.5% vs 50% THID) at 25% load and 13% better (12% vs 25% THID) at 50% load.
- **Power Factor:** Better to equal performance for loads 50-100%.*

A 6-pulse drive with a Matrix AP harmonic filter has a number of additional benefits over the 18-pulse drive: smaller equipment size and weight, lower price, and shortened lead time/increased availability of drives and corresponding replacement parts.

*The Matrix AP harmonic filter exhibited a reduced leading power factor under light loads. While advantageous in some circumstances, a capacitor contactor option may be used to remove the filter capacitors from the circuit and eliminate this condition.

**Background**

The proliferation of variable frequency drives (VFDs) has brought increased attention to harmonic effects created by drives: a standard 6-pulse drive without any harmonic mitigation technology may interfere with neighboring equipment, reduce equipment life, and negatively impact the utility power quality. Under some circumstances the total harmonic current distortion (THID) may approach the level of the fundamental current. Drive manufacturers offer a low harmonic, 18-pulse drive to combat these effects. An alternative solution is the use of a traditional 6-pulse drive equipped with a passive harmonic filter; however, typical passive harmonic filters experience reduced effectiveness at loads less than 100%. With the introduction of adaptive passive technology, the Matrix AP harmonic filter maintains strong harmonic filtering performance across a wide range of loads. This paper compares the performance of a 100 HP 18-pulse drive with the performance of a standard 100 HP 6-pulse drive equipped with a 128 amp Matrix AP 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. 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.

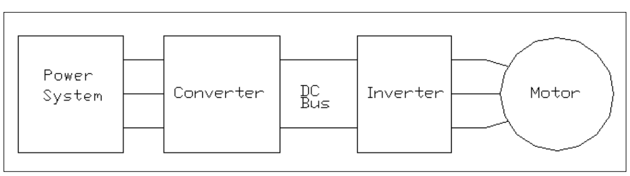


*Figure 1 Basic VFD block diagram*

Figure 2 shows the power system and converter for a 6-pulse 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]:

$$h = (np \pm 1) \qquad (1)$$

Where $n$ = 1, 2, 3… & $p$ = pulse number

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

Figure 3 shows a vector representation of the three phase power system voltages. 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 very balance power to the converter.

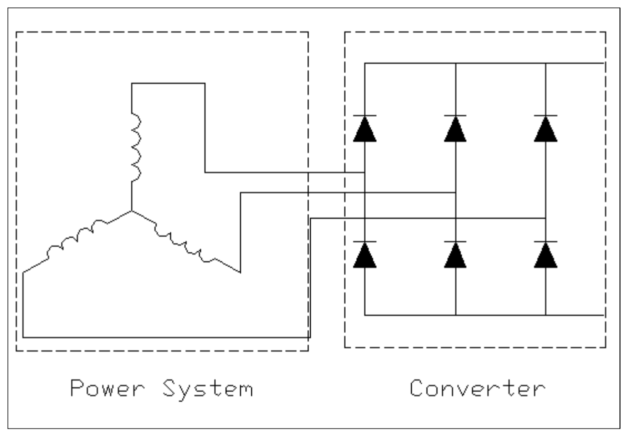


*Figure 2 6-pulse power system and converter*

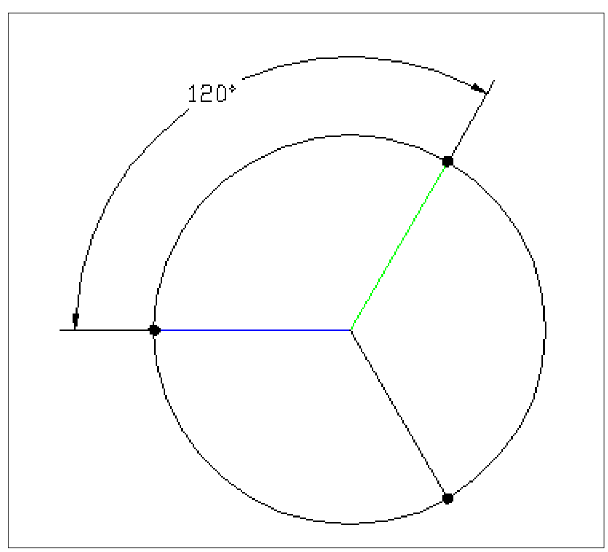


*Figure 3 Three phase power system voltage vector representation*

## 18-Pulse Overview

Figure 4 shows a 9-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 each other. There are eighteen rectifiers in the converter. Applying equation (1), the input current would only have harmonic components at the following multiples of the fundamental frequency: 17, 19, 35, 37, 53, 55, etc. with a balanced system.

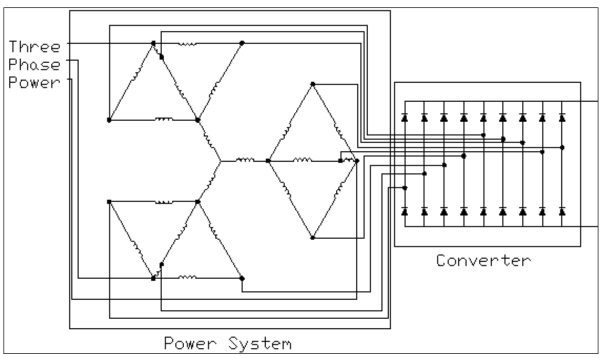


*Figure 4 Nine phase power system and 18-pulse converter*

Note that the 5$^{th}$, 7$^{th}$, 11$^{th}$, and 13$^{th}$ 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.

Figure 5 shows two patented vector representations of methods used to form a 9-phase power system [6] [2]. The three phases are represented by the blue, black and green lines. A 9-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 each other 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 design of good 9-phase transformer windings is largely a trigonometry problem and is complicated by integer amount of turns available for the transformer design that results in discrete amounts of voltage available. The leakage inductance between transformer windings also needs to be balanced to control voltage regulation. There are an infinite number of winding configurations possible to create the nine phases required for an 18-pulse system.

A purely 18-pulse system alone does not provide harmonic filtering. The reduction in THID relies solely on cancelling the harmonics. Therefore any imbalance of system voltages in either magnitude or phasing, or harmonic voltage distortion is not mitigated. Many of these imbalances originate from within the nine phase transformer itself.

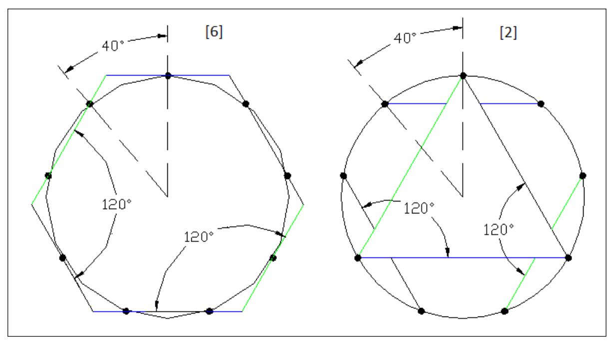


*Figure 5 18-pulse vector representations of transformer windings*

The system used for testing includes an 8% impedance reactor, 9-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% to 10% line reactor on the line side of the transformer.

## Matrix AP Overview

Figure 6 shows a single phase schematic representation of an MTE Matrix AP filter with a 6-pulse drive. It consists of a patented [4] [5], integrated, adaptive passive Harmonic Mitigating Reactor (HMR) and a capacitor network. The Matrix AP adaptive passive filter is used between a standard three phase power system and 6-pulse drive.

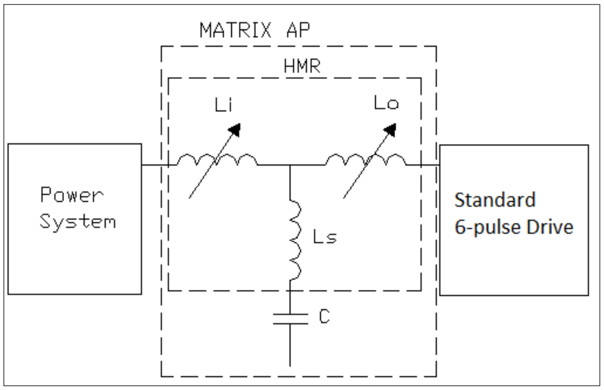

*Figure 6 Matrix AP filter diagram*

$L_s$ 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. $L_o$ reduces the voltage boost due to the capacitors. Both $L_i$ and $L_o$ also reduce the THID by adding wideband line filtering impedance.

The inductance of $L_i$ and $L_o$ also vary depending on load levels. At reduced load the inductance increases to improve THID performance. The use of this adaptive passive characteristic allows the use of less capacitance and improved power factor at reduce loads without sacrificing THID performance.

**Power Loss Comparison**

Many drive manufacturers convert their standard 6-pulse drive offering to 18-pulse drives. Figure 7 shows one method of conversion. 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 Matrix AP filter. Table 1 and Figure 8 show the comparison of the 18-Pulse added component losses of two manufacturers to MTE's Matrix AP. The data shows that losses from the Matrix AP harmonic filter are 34 to 74% less than those from added 18-pulse components.

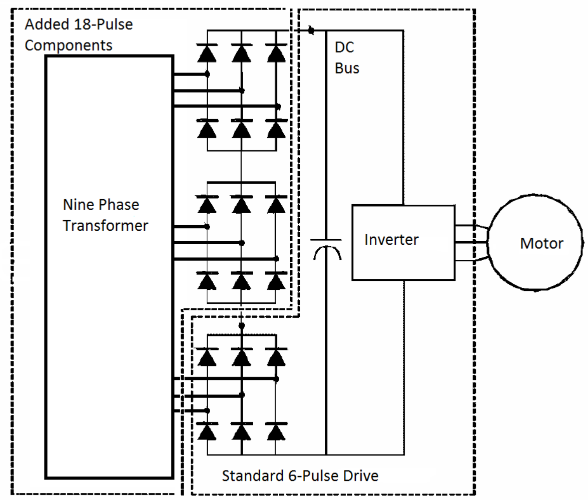

*Figure 7 6-pulse drive conversion to 18-pulse*

*Table 1 Power loss comparisons*

| Drive (HP) | MTE Matrix AP Power Loss (W) | Additional Drive Components Manufacturer #1 Power Loss (W) | Additional Drive Components Manufacturer #1 Matrix AP Loss Reduction | Additional Drive Components Manufacturer #2 Power Loss (W) | Additional Drive Components Manufacturer #2 Matrix AP 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% |
| 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% |

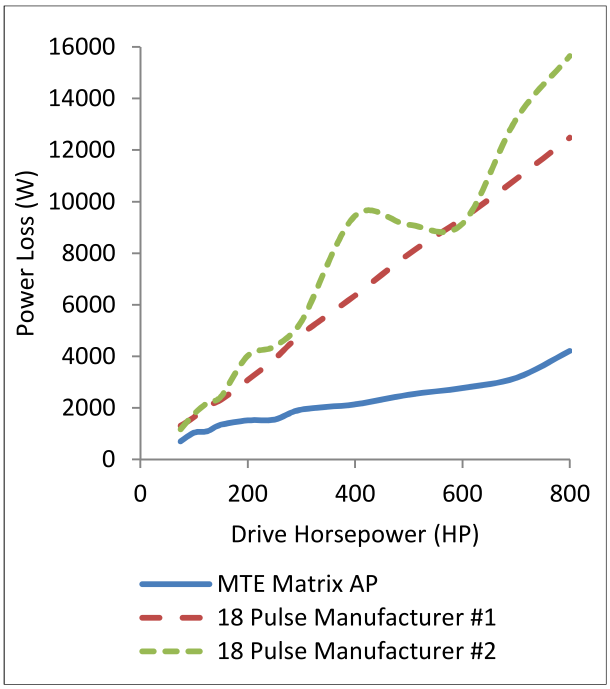


*Figure 8 Power loss comparisons*

**Efficiency Comparison**

The percent filter efficiency is calculated using the following equation, Eq. (2), since both harmonic mitigation techniques have near unity power factor at full load:

$$\%\,Efficiency = \frac{P_{out}}{P_{in}}\times 100 = \frac{(V_{in}\times I_{in}\times\sqrt{3}) - P_{filter}}{(V_{in}\times I_{in}\times\sqrt{3})}\times 100 \quad (2)$$

Figure 9 shows a comparison of additional component losses from Table 1 of 18-Pulse product lines of two manufacturers to MTE's Matrix AP efficiencies. The Matrix AP filter typically is greater than 99% efficient whereas the typical 18-pulse solution is about 98%. In all cases the Matrix AP filter is more efficient than the 18-pulse drive added components.

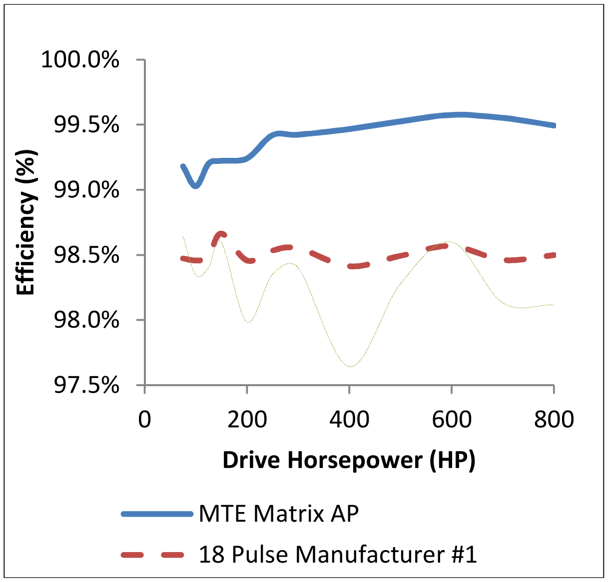


*Figure 9 Percent efficiency of the added 18-pulse components and Matrix AP*

**THID Performance Comparison**

The total harmonic current distortion (THID) performance of a typical 100 HP, 18-pulse drive and a 6-pulse drive with a Matrix AP filter was compared. Figure 10 compares the actual test data between an 18-pulse drive and a Matrix AP filter. The total harmonic voltage distortion (THVD) was about 1.5% for most of the test conditions. At full load both harmonic mitigation techniques performed under 5% THID, the most stringent IEEE 519 requirement for general distribution systems. The Matrix AP filter had better THID performance at reduced load.

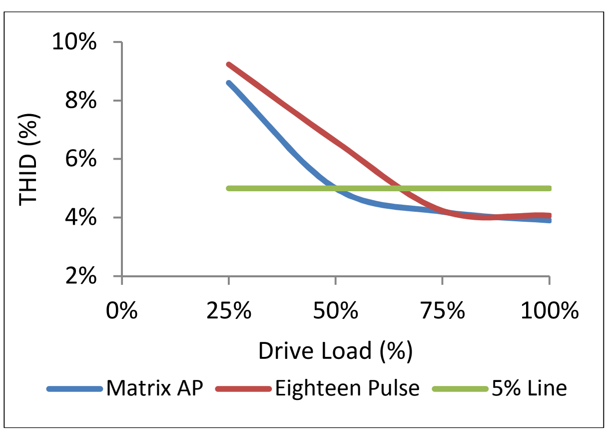


*Figure 10 Matrix AP with 6-pulse and 18-pulse THID versus Load*

Figure 11 shows the harmonic mitigation performance of a standard 6-pulse drive with a Matrix AP 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 THID for the 18-pulse system was considerably worse than the standard 6-pulse drive with a Matrix AP filter. The 18-pulse had 50% THID compared to 17.5% THID for the standard 6-pulse drive with a Matrix AP filter at 25% load.

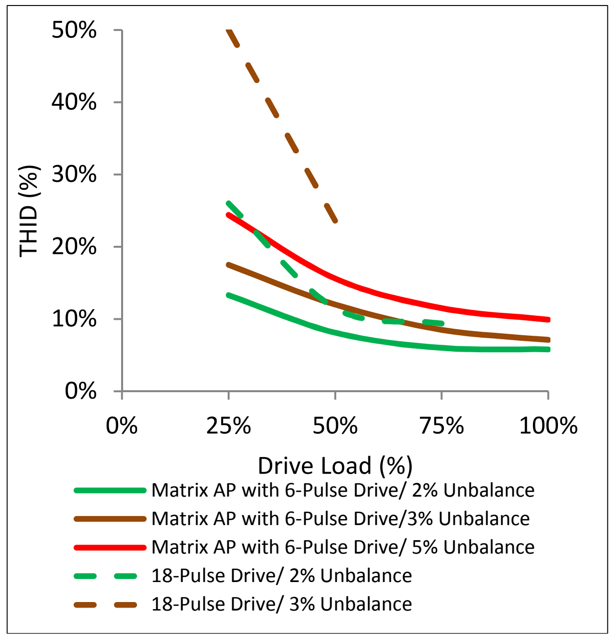


*Figure 11 Matrix AP with 6-pulse drive and 18-pulse THID with system voltage imbalance*

**Power Factor Performance Comparison**

The power factor performance of a typical 100 HP 18-pulse drive and a 6-pulse drive with MAPP0128D 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 Matrix AP 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.

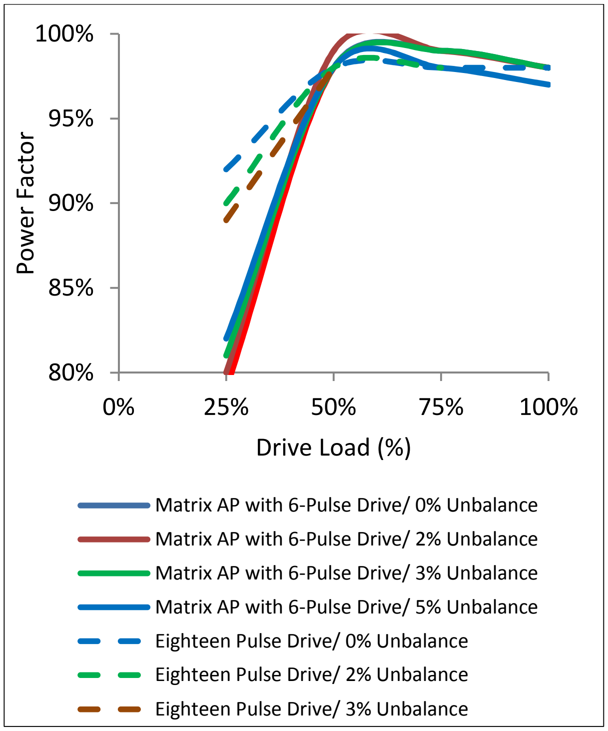


*Figure 12 Power factor versus load*

The reduced power factor at reduced loads for the Matrix AP adaptive passive 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 lagging power factor. The power factor in effect is adjusted closer to unity. If this is not advantageous, standard options are available to disconnect the capacitors at light loads to increase power factor either by automatic sensing of load levels or manually by the user. Figure 13 shows MTE's Matrix AP with automatic contactor option. The load current is sensed and the capacitors are connected at 20% load and disconnected at 35% load. This hysteresis prevents chattering of the contactor.

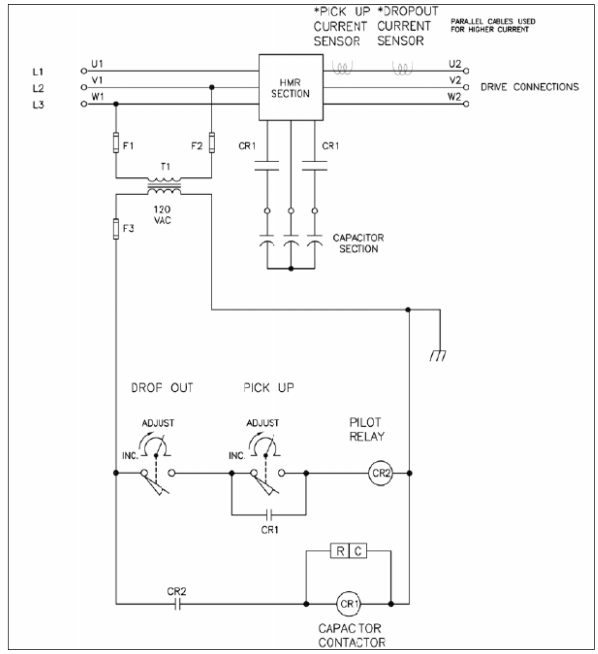


*Figure 13 MTE Option -009 capacitor disconnect option schematic*

## 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 Matrix AP 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 HMR of the MAPP0128D and is considerably heavier.

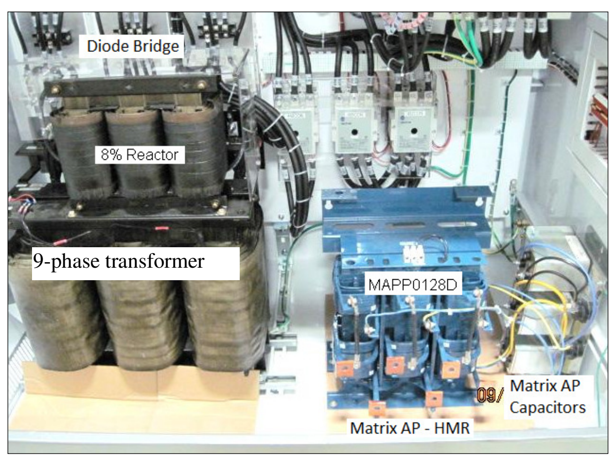


*Figure 14 100 HP 18-pulse transformer and MAPP0128D*

*Table 2 100 HP magnetics size comparisons*

| | 18-Pulse Transformer/ Reactor | MAPP0128D HMR |
|---|---|---|
| Height (in) | 28 | 15.25 |
| Width (in) | 19 | 20 |
| Depth (in) | 12 | 11.7 |
| Volume ($in^3$) | 6384 | 3569 |

**Conclusion**

The 6-Pulse drive with Matrix AP harmonic filter outperformed the 18-pulse drive in the following technical specifications:

- **Power loss:** Approximately 665 less watts consumed.
- **Overall efficiency:** 0.5% more efficient (99.0% vs. 98.5%).
- **Harmonic performance under balanced line conditions:** 1-2% better THID performance for loads 25-75% and equal performance for loads greater than 75%.
- **Harmonic performance under line imbalance conditions:** Significantly better performance. For example under 3% line imbalance, performance was 32.5% better (17.5% vs 50% THID) at 25% load and 13% better (12% vs 25% THID) at 50% load.
- **Power Factor:** Better to equal performance for loads 50-100%.*

A 6-pulse drive with a Matrix AP harmonic filter has a number of additional benefits over the 18-pulse drive: smaller equipment size and weight, lower price, and shortened lead time/increased availability of drives and corresponding replacement parts.

* The Matrix AP harmonic filter exhibited a reduced leading power factor under light loads. While advantageous in some circumstances, a capacitor contactor option may be used to remove the filter capacitors from the circuit and eliminate this condition.

**References**


[1] Hink, Karl M. “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.

[4] Shudarek, Todd A. “Multiple Three-phase Inductor with a Common Core.” US Patent 7,142,081. 28 Nov 2006.

[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.