18-PULSE DRIVES AND VOLTAGE UNBALANCE

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ABSTRACT

Eighteen-pulse drives are frequently specified by consulting engineers for heating, ventilating and air conditioning applications because of their theoretical ability to reduce harmonic current distortion, but very little information has been published showing how eighteen-pulse drives perform under actual operating conditions with unbalanced input line voltages. This paper presents test data which demonstrate that eighteen-pulse drives do not achieve the level of harmonic mitigation most engineers expect and that these drives may not meet the requirements of IEEE-519 under practical operating conditions. The actual performance of eighteen-pulse and six-pulse drives is compared to the performance of a six-pulse drive fed by a Matrix Harmonic Filter. The Matrix Harmonic Filter provides superior harmonic mitigation at lower cost.

In the mid 1960s when power semiconductors were only available in limited current ratings, eighteen-pulse drives provided a simpler and more cost effective approach to achieving higher current ratings than direct paralleling of power semiconductors. With this approach a drive could be easily constructed with almost three times the horsepower available from the largest six pulse converter. The technique is still employed today in very large drive applications. In addition eighteen pulse drives have become a popular approach to harmonic mitigation.

Eighteen pulse rectifiers can be constructed to operate in parallel or series. In a series configuration, three six-pulse rectifiers, each generating one third of the DC link voltage, are series connected. The series connection avoids, issues associated with current sharing and eliminates the need for an interphase reactor. For applications where harmonic mitigation rather than high current ratings are the objective, this solution is much simpler to implement than the parallel connection. Using the series rectifier connection, it is very easy to construct an eighteen-pulse drive from a standard six-pulse drive if the six-pulse drive has its DC bus terminals available or permits access to one side of the DC bus. Many standard AC drives provide terminals in the DC bus to accommodate an external DC link choke. These same terminals can be used to add two external rectifiers converting the drive to eighteen-pulse operation. The net result is a system solution well within the means of many system integrators.

A typical diagram of a series connected eighteen pulse drive constructed from a standard six-pulse drive, two external rectifiers and a conventional 18 pulse isolation transformer appears in figure 1. The drive has terminals available to connect a DC link choke. These terminals are used to connect the two external rectifiers in series with the drives internal rectifier. The eighteen pulse transformer is designed to provide one third the normal input voltage to each of the three rectifiers at a 20 degree phase displacement from each other. The 20-degree phase shift is obtained by phase shifting the transformers secondary windings. The circuit in figure 1 simply uses an isolation transformer with a delta primary, and three delta connected secondary windings, one shifted + 20 degrees, one shifted -20 degrees and one in phase with the primary.

The primary current in the transformer is the sum of each six-pulse rectifier or an eighteen-pulse wave form.

Theoretical input current harmonics for rectifier circuits are a function of pulse number and can be expressed as:

$h = (np \pm 1)$ where $n = 1, 2, 3, \ldots$ and p = pulse number

For a six-pulse rectifier, the input current will have harmonic components at the following multiples of the fundamental frequency.

5, 7, 11, 13, 17, 19, 23, 25, 29, 31, 35, 37, 41, 43, 47, 49, 53, 55, etc.

For the eighteen-pulse system shown in figure 1, the input current will have theoretical harmonic components at the following multiples of the fundamental frequency:

17, 19, 35, 37, 53, 55, etc.

.
Note that the 5^{th} and 7^{th}, 11^{th} and 13^{th} harmonics are absent in the theoretical eighteen-pulse system. Since the magnitude of each harmonic is proportional to the reciprocal of the harmonic number, the eighteen-pulse system has a lower theoretical harmonic current distortion.

There are numerous transformer connections that can be used to achieve the 20 degree phase displacement between the input voltages to the three rectifiers. Figure 2 shows an eighteen pulse drive using a transformer with a delta primary and three phase displaced wye secondary windings. A number of drive manufacturers have addressed the cost issues associated with an eighteen pulse phase shifting isolation transformer and have created novel lower cost autotransformer designs to achieve the required phase displacement between the three converters.

There are many fine textbooks and articles in which rectifier circuits are examined and analyzed in detail. However, most of the analysis is performed under the assumption of balanced three-phase line voltages. Our practical experience suggests that this assumption is not valid for many industrial and commercial power systems, particularly systems with nonlinear loads. As we traveled around the United States working primarily with drive applications, our impression was that most power systems were operating with 1% to 3% unbalance at the point of utilization.

ANSI C84.1 – 1995 defines percent voltage unbalance as:

$$\frac{100 \text{ X (max. deviation from average voltage)}}{\text{(Average Voltage)}}$$

This same standard also reports that based on field surveys, 98% of power systems are within 0 - 3.0% voltage unbalance range and 66% are within 0 - 1.0% unbalance at the point of common coupling. The standard recommends that electric supply systems be designed and operated to the limit of a maximum voltage unbalance to 3% when measured at the electric utility revenue meter under no-load conditions. Load unbalance within the building power distribution system adds to the utility unbalance at the point of utilization.

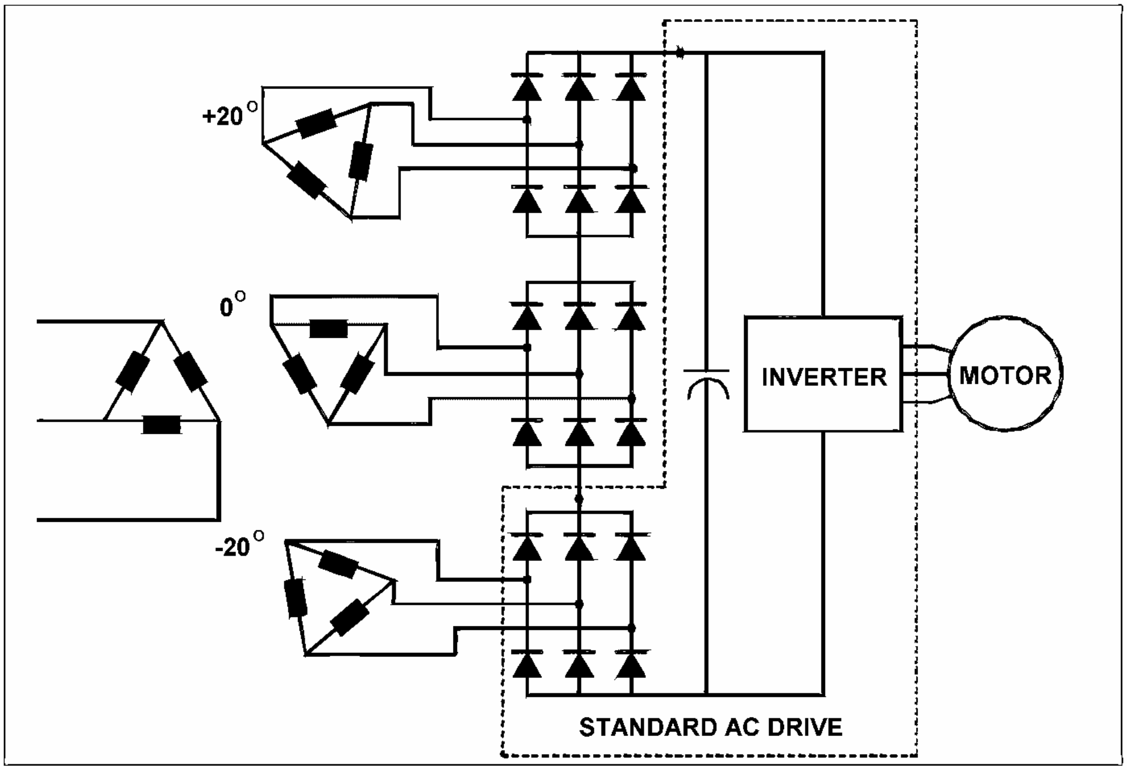

Figure 1

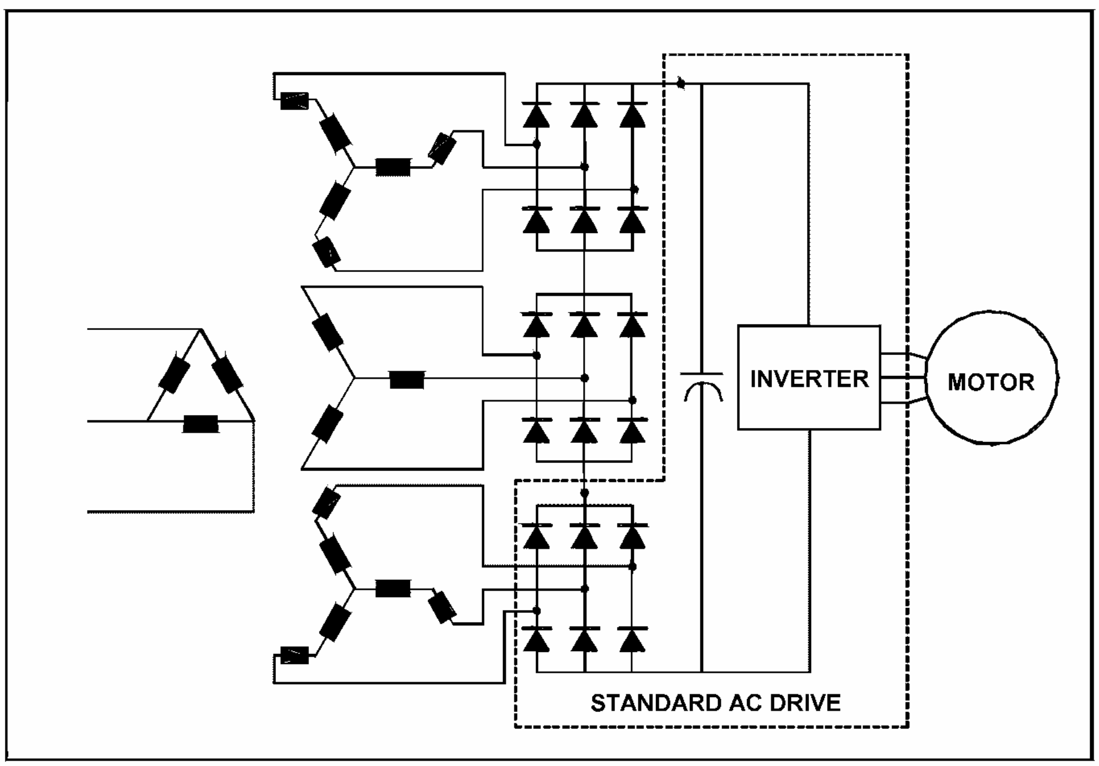

Figure 2

To determine how an eighteen-pulse drive system operates under unbalanced line voltage conditions, we constructed a 30 HP eighteen-pulse drive from a conventional isolation transformer and standard six-pulse drive using the series bridge connection shown in figure 1. An auto transformer could have been used in place of the isolation transformer. The auto transformer costs less and requires less mounting space, but the isolation transformer was selected because it provides better performance and is readily available as a modified standard transformer. Care was taken in the physical construction of the transformer to balance the leakage reactance and output voltage of the three secondary windings. The system was tested with line voltage unbalance ranging from 0% to 3% and with loads ranging from 5% to 100%. The input total harmonic current distortion, THID, is shown in figure 3. THID varied from 7.4% at full load with balanced line voltages to 59% at 30% load with a 3% unbalance. The data show that the harmonic performance of eighteen-pulse drives degrades rapidly with increasing line voltage unbalance and decreasing load. Simply focusing on harmonic performance under the best operating conditions, perfectly balanced line voltages and full load, is not a useful indicator of performance under practical operating conditions. In heating, ventilating and air conditioning applications where drives will operate for long periods of time at 30% to 60% load eighteen pulse drives to not meet expectations.

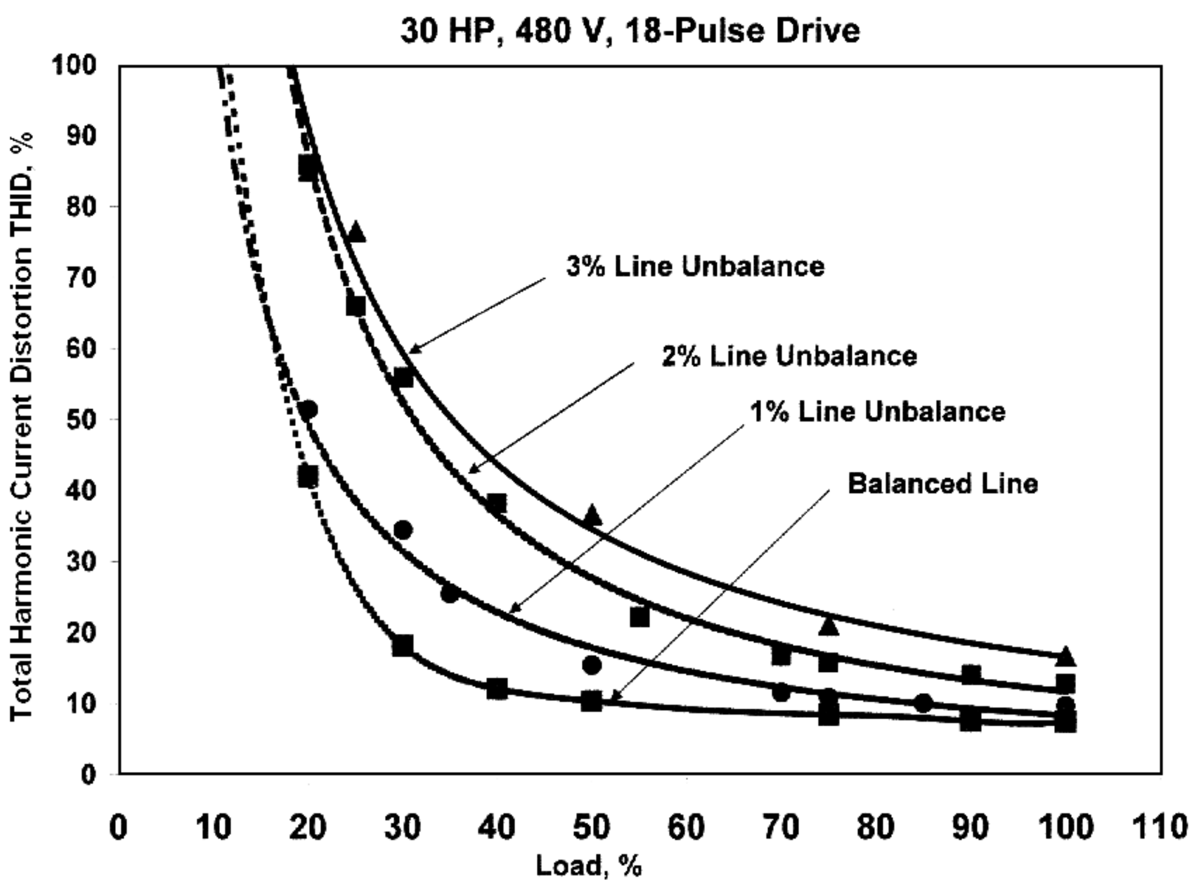

Figure 3

Obviously, any unbalance in the eighteen-pulse transformer's leakage reactance and output voltage will degrade performance. Unfortunately perfect transformers can not be built. Output voltage depends on turns ratios which are limited to plus or minus one turn. As a result the output voltage of the three secondary windings cannot be perfectly balanced. Leakage reactance is a function of coil position and volume. Clever mechanical design of the transformer windings will help to minimize the differences in leakage reactance between the three groups of secondary windings but perfect balance can not be achieved. Data for the transformer used in this test appears in Tables 1and 2
.

Transformer Design

Secondary Winding Phase Shift Degrees	Leakage Reactance %	Nominal Output Voltage Based on Turns Ratios Volts
0	3.67	160.00
-20	4.73	160.50
+20	5.33	160.50

Table 1

Transformer Full Load Data

Secondary Winding Phase Shift Degrees	Secondary Phase Voltage At Full Load Volts				Unbalance Per Secondary Group %	Unbalance Across Secondary Groups %
	A	B	C	Average		
0	154.3	154.4	154.1	154.26	0.10	
-20	157.9	157.0	157.6	157.50	0.32	
					.	
+20	156.6	155.4	156.9	156.30	0.57	
			Average	156.02		1.12

Table 2

The addition of 5% line reactors at the input to each of the three rectifiers results in a significant improvement in the operation of the 18-pulse drive. Figure 4 shows the impact of reactors for a 3% line voltage unbalance. For comparison figure 4 also shows THID for the same 30HP drive operating with a six-pulse rectifier and 5% input line reactor under same line voltage conditions. THID for the 6-pulse system varied from 29% at full load to 87% at thirty per cent load. THID for the 18-pulse system with input line reactors varied from 8.4% at full load to 42% at thirty per cent load. The harmonic performance of the eighteen-pulse drive is superior to a six-pulse drive over the normal operating range of loads. However, for most applications the 18-pulse system requires the use of a input line reactor for each of the three rectifiers to achieve acceptable performance under practical operating conditions.

It is interesting to compare the performance of the eighteen-pulse drive with a standard six-pulse drive fitted with an MTE Matrix Harmonic Filter under similar conditions of unbalanced line voltages. The Matrix Harmonic Filter is a type of low pass harmonic filter designed to work with standard six-pulse drives. A Matrix Harmonic Filter was tested feeding a 30 HP six-pulse drive. This system was tested with line voltage unbalance ranging from 0% to 3% and with loads ranging from 5% to 100%. The input total harmonic current distortion, THID, is shown in figure 5. THID varied from 4.7% at full load with balanced line voltage to 9% at thirty per cent load with a 3% line voltage unbalance. The low pass filter provides better harmonic performance than the eighteen-pulse system throughout the load range and is significantly less sensitive to voltage unbalance. A summary of the data for a 3% line unbalance appears in the Table 3.

THID with 3% Line Voltage Unbalance

Drive Description	**Load**	
	100%	**30%**
6-pulse with 5% Reactor	29	87
18- Pulse	16	59
18-Pulse with 5% Reactors	8.4	42
6-Pulse with Matrix Filter	4.7	9.0

Table 3

Conclusion

Drives are applied in heating, ventilating, and air conditioning applications because loads are variable and users demand energy efficiency and comfort. Varying loads result in load unbalances within building power distribution systems which add to the utility line voltage unbalance at the point of common coupling. Harmonic mitigation techniques which are not effective with line voltage unbalances of 1% to 3% at the point of utilization will not as a practical matter achieve useful results. The data in this report show that a standard six-pulse drive fed from a low pass Matrix Filter provides superior harmonic performance to an eighteen-pulse drive in applications with variable loads and line voltage unbalances ranging from 0% to 3%.

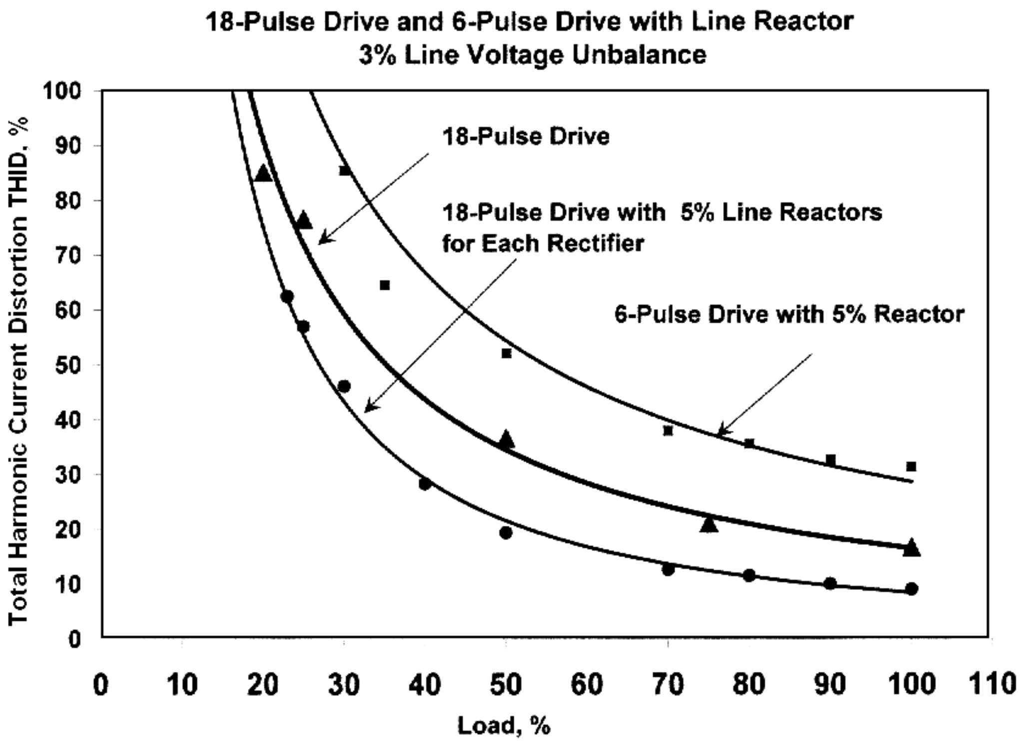

Figure 4

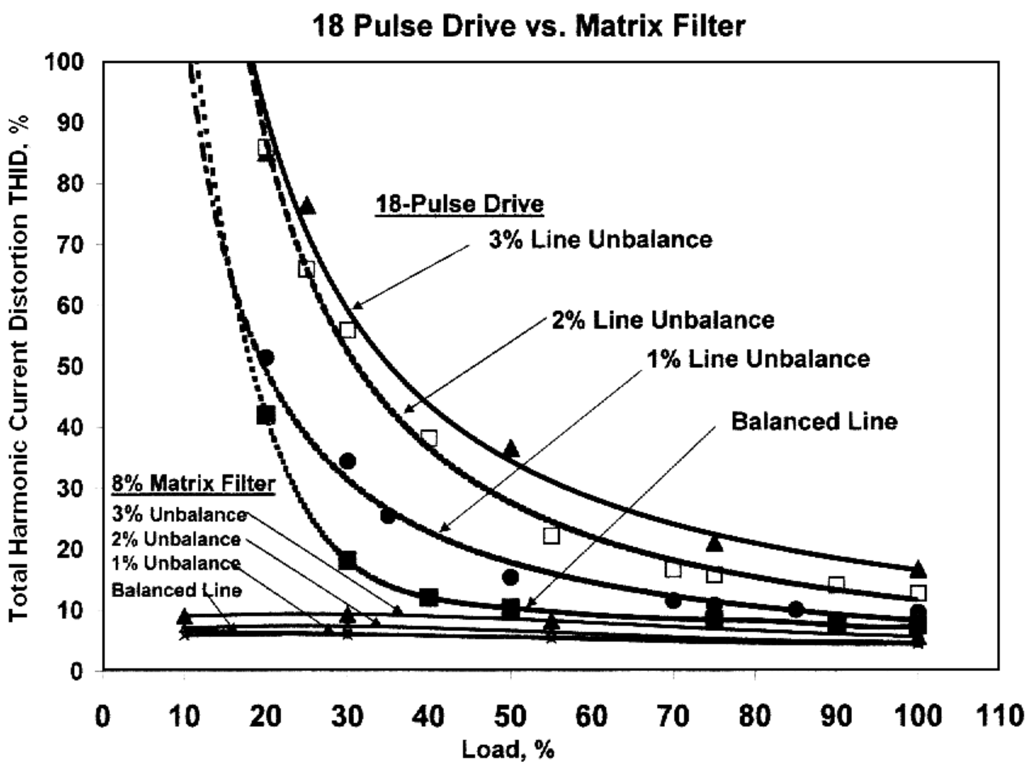

Figure 5