Performance of Harmonic Mitigation Alternatives

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Abstract: *Users of variable frequency drives often have strict demands placed on them to mitigate harmonic distortion caused by non-linear loads. Many choices are available to them including line reactors, harmonic traps, 12-pulse rectifiers, 18-pulse rectifiers, and low pass filters. Some of these solutions offer guaranteed results and have no adverse effect on the power system, while the performance of others is largely dependent on system conditions. Certain techniques require extensive system analysis to prevent resonance problems and capacitor failures, while others can be applied with virtually no analysis whatsoever. In some cases harmonic mitigation technique decisions were based on a technical misunderstanding, lack of information, theoretical data or on invalid assumptions.*

This paper explains the theory of operation of various passive harmonic mitigation techniques and demonstrates their typical real life performance. It takes the guesswork out of harmonic filtering by demonstrating the typical performance of various harmonic mitigation techniques and offering a quantitative analysis of alternatives for real life VFD operating conditions.

1 SOURCE REACTANCE

The magnitude of harmonic currents in an individual non-linear load depends greatly on the total effective input reactance, which is comprised of the source reactance plus added line reactance. Given a six pulse rectifier with dc bus capacitor, one can predict the resultant input current harmonic spectrum based on the input reactance. The lower the source reactance, (the more stiff the power source), the higher the harmonic content will be.

1.1 Typical Harmonic Performance

The typical harmonic spectrum data for a six-pulse rectifier load fed by a stiff power source (0.25% and 0.5% impedance) is as follows:

h	**0.25% reactance**	**0.50% reactance**
5th	102%	78%
7th	92%	58%
11th	26%	18%
13th	14%	10%
17th	10%	7%
19th	8.5%	6%
23rd	7%	5%
25th	3%	2.3%
THID	**141%**	**100%**

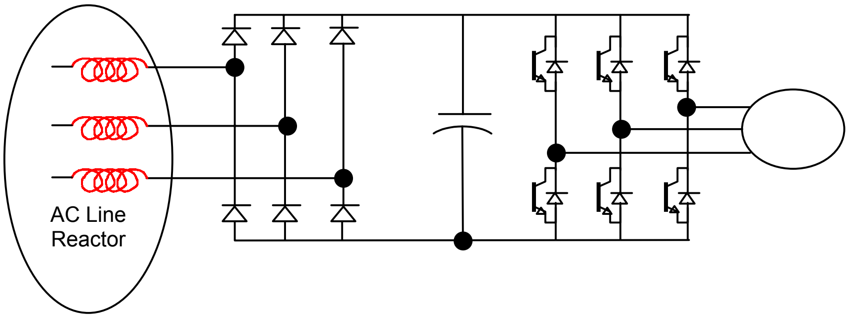
(THID = total harmonic current distortion)

Since power distribution transformers frequently have impedance ratings between 1.5% and 5.75%, one would expect that source impedance is often relatively high and that harmonics should therefore be quite low. However, transformer impedance ratings are based on transformer rated KVA, so when the transformer is partially loaded, the effective impedance of the transformer, relative to the actual load, is proportionately lower, [ie: 1.5% impedance at 30% load = 0.5% effective impedance].

2 LINE REACTORS

The use of AC line reactors is a common and economical means of increasing the source impedance relative to an individual load. Line reactors are connected in series with the six pulse rectifier diodes at the input to the VFD, as shown in *Fig 1*.

Fig 1.



2.1 Typical Harmonic Performance of Reactors

The typical harmonic spectrum data for a six pulse VFD load fed by a power supply with an effective source reactance of 3%, 5% and 8% looks as follows:

h	**3 % reactance**	**5% reactance**	**8% impedance 3% dc choke & 5% ac reactor**
5th	39%	32%	27%
7th	17%	12%	9%
11th	7%	5.8%	4.5%
13th	5%	3.9%	3.2%
17th	3%	2.2%	1.8%
19th	2.2%	1.7%	1.4%
23rd	1.5%	1%	0.8%
25th	1%	0.9%	0.75%
THID	**44%**	**35%**	**29%**

These data represent the harmonics measured at the input to the six pulse rectifier and will reduce to lower percentages when measured further upstream, provided there are other linear loads operating on the system. If 20% of the system load is comprised of VFDs with 5% input impedance, and 80% has linear loads, the harmonic current distortion at the VFD input will be 35% THID, but only 7% at the supply transformer secondary. Typically costing less than 3% of the motor drive system, line reactors are the most economical means of reducing harmonics. Practical ratings can achieve 29% to 44% THID at the input to the six pulse rectifier (usually lower THID at the transformer secondary), at full load operation. Their typical watts losses are less than 1% of the load.

Fig. 2 illustrates the input current waveform of a six pulse rectifier supplied by a power source of (a) 0.5% effective impedance and (b) 3% effective impedance.

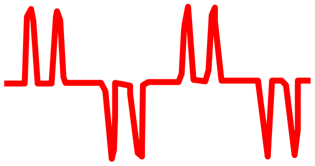
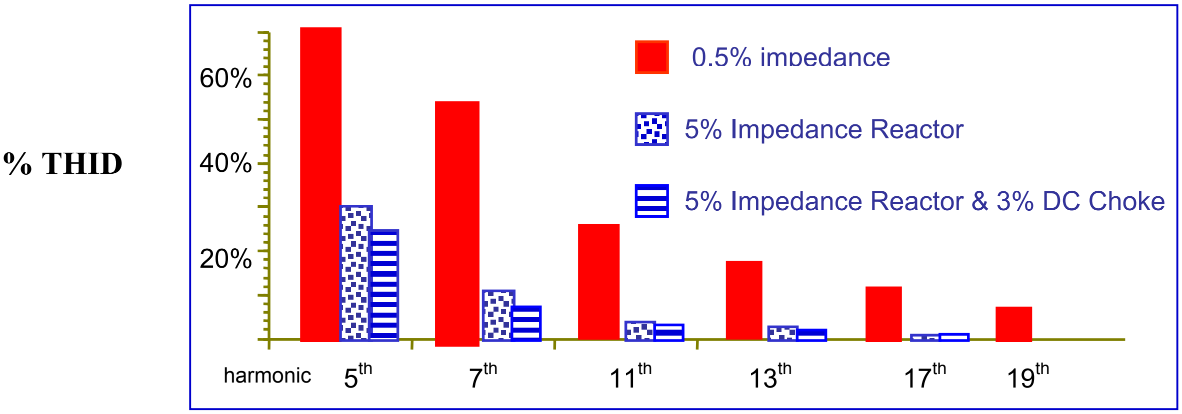


Fig. 2(a) Input Current waveform of 6-pulse rectifier w/0.5% impedance

Fig. 2(b) Input current of 6-pulse rectifier w/ 3% impedance

Fig. 3 illustrates the typical harmonic spectrum for a six-pulse rectifier with 0.5%, 5% or 8% effective source impedance, (8% = 5% line reactor + 3% DC bus choke).



2.2 Reactor Performance at Light Load

The harmonic mitigation performance of reactors varies with load because their effective impedance reduces proportionately as the current through them is decreased. At full load, a 5% effective impedance reactor achieves harmonic distortion of 35% THID, however, at 60% load it's effective impedance is only 3% {0.6 x 5% = 3%}, and harmonics will be 44% THID. Although THID increased as a percentage, the total rms magnitude of harmonic current actually decreased by nearly 25% {1 – ((.6 x 44%) / 35%) = 24.5%}. Since voltage distortion at the transformer secondary is dependent upon the magnitude and frequency of current harmonics that cause harmonic voltage drops across the transformer's internal reactance, the voltage distortion (THVD), at the transformer secondary, actually decreases as this load is reduced.

3 TUNED HARMONIC TRAP FILTERS

3.1 Harmonic Trap Performance

Tuned harmonic filters (traps) involve the series connection of an inductance and capacitance to form a low impedance path for a specific (tuned) harmonic frequency. The filter is connected in parallel (shunt) with the power system to divert the tuned frequency currents away from the power source.

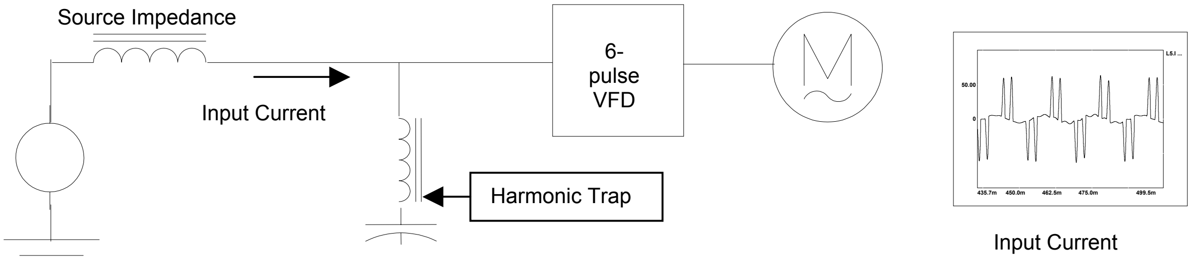
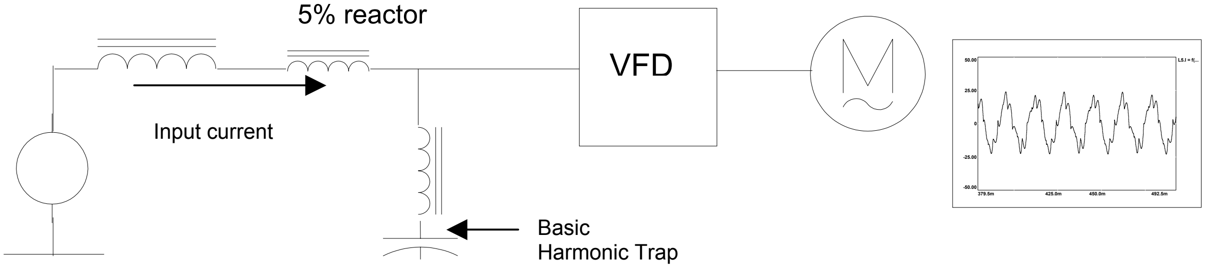


Fig. 4 (with 0.25% source impedance)

Unlike line reactors, harmonic traps do not attenuate all harmonic frequencies. Most often they are tuned for 5th harmonic mitigation. If applied to a low impedance power source, as demonstrated in *Fig. 4*, the harmonic mitigation performance of this filter is quite limited and the benefit of this filter may be unrecognizable. To improve the performance of a trap filter, a 5% impedance line reactor may be connected in series with the input to the filter, as shown in *Fig. 5*.



THID = 24.5%

Fig. 5 (with 0.25% source impedance)

If the VFD has internal line reactance, then harmonic trap performance may improve slightly. The typical residual THID for a six pulse rectifier with a tuned 5th harmonic trap is between 20% to 30% at full load, provided there is significant source impedance. The watts loss of this type of filter can be 2-3% of the load and it can cost ten times the price of a line reactor. Tuned harmonic traps will alter the natural resonant frequency of the power system and may cause system resonance, increasing specific harmonic levels. They may attract harmonics from other non-linear loads sharing the same power source and must be increased in capacity to accommodate the addition of new loads. For best results, a power system study should be performed to determine the magnitude of harmonics to be filtered (from all loads), the power system resonant frequency and the impact of future addition of loads.

3.2 Harmonic Traps at Light Load Conditions

Harmonic traps achieve their best attenuation of harmonics at full load conditions. At light load, the resultant THID can increase significantly and may be no better than the performance normally achieved with a line reactor. *Fig. 6* demonstrates the input current waveform of a six pulse rectifier with a tuned 5th harmonic trap, operating at 50% load, when the line voltages were 3% unbalanced. Notice the similarity to a non-linear single phase load.

Fig. 6 Input current waveform for a Six-pulse rectifier with 5th harmonic tuned harmonic filter, measured at 50% load, and with 3% line voltage unbalance and 0.25% source impedance.

Harmonic current distortion = 139% THID

Fig. 6

4 12-PULSE RECTIFICATION

4.1 Theory of performance

Twelve pulse rectifier configurations have been used for applications demanding lower harmonic levels than can be achieved using either traps or reactors. The theoretical benefits of 12-pulse rectification include cancellation of 5th, 7th, 17th, 19th, etc harmonics. However, real life harmonic mitigation resulting from the use of twelve pulse rectifiers can be quite different than one's theoretical expectations. The most common method of twelve pulse rectification involves the parallel connection of two bridge rectifiers, each fed by a 30 degrees phase shifted transformer winding. Often the transformer has a single primary winding and dual secondary windings. One secondary winding is a delta and the other is connected in wye configuration to achieve 30 degrees of phase shift between secondary voltages.

"A major design goal in multipulse operation is to get the converters, or converter semiconductor devices, to share current equally. If this is achieved, then maximum power and minimum harmonic currents can be obtained."(1) In order to achieve cancellation of harmonics, the two individual bridge rectifiers must share current equally. This can only be achieved if the output voltage of both transformer secondary windings are exactly equal. "Because of differences in the transformer secondary impedances and open circuit output voltages, this can be practically accomplished for a given load (typically rated load) but not over a range in loads."(2) Typical losses of a twelve pulse transformer are 3% to 5% of the transformer KVA rating.

4.2 Twelve Pulse Performance with Balanced Line Voltages

Fig. 7 illustrates actual measurements of input current harmonic distortion for a twelve pulse rectifier supplied from a balanced three phase voltage source while operating at full load conditions. For test purposes, the transformer had a delta primary with delta and wye secondary windings (each rated at one-half line voltage). To obtain "best case" results, the bridge rectifiers were series connected so equal DC current flowed in each converter. The data shows that when the current through both sets of rectifiers is equal, harmonics can be as low as 10% to 12% THID at full load. Current sharing reactors will help parallel connected bridge rectifiers to share current equally. While current sharing reactors are highly recommended for twelve pulse configurations, they are usually omitted in the interest of minimizing cost. Even with balanced current however, harmonic distortion can increase appreciably at light load conditions.

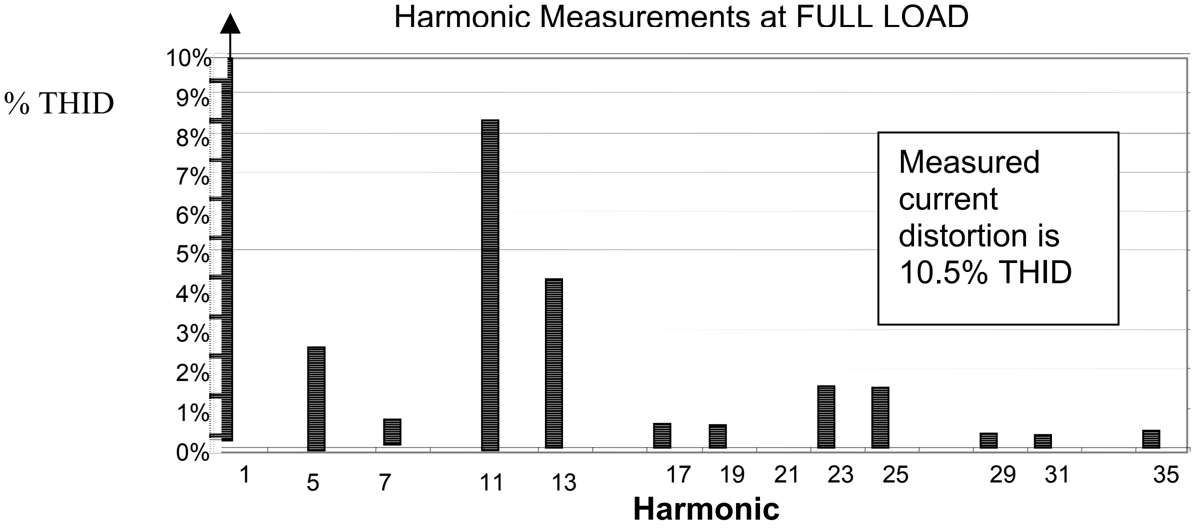


Fig. 7 Harmonic spectrum for 12-pulse rectifier, measured while *operating at full load*, when line voltages were balanced.

4.3 Twelve-Pulse Performance when Line Voltages are Not Balanced

Practical aspects of multipulse transformer winding configurations and circuit parameters make it unlikely that perfect balance can be achieved between all six secondary voltages, especially when the load is varied from *full load* to *no load* conditions. Additionally, facility power system voltage unbalance is common (according to ANSI C84.1, 34% of facilities surveyed in the USA experienced between 1% and 3% voltage unbalance at the service entrance point and even greater unbalance in the facility and closer to the loads). It is interesting to note that occasionally 12-pulse drives are sold without the transformer, shifting responsibility for the transformer specification and system performance from the supplier to the user or installer. *Fig. 8* demonstrates the impact of both line voltage unbalance and light loading conditions on the harmonic mitigation performance of twelve pulse rectifiers. Even with perfectly balanced line voltages, the resultant %THID increases as the load is reduced (ie: 23% THID at 20% load).

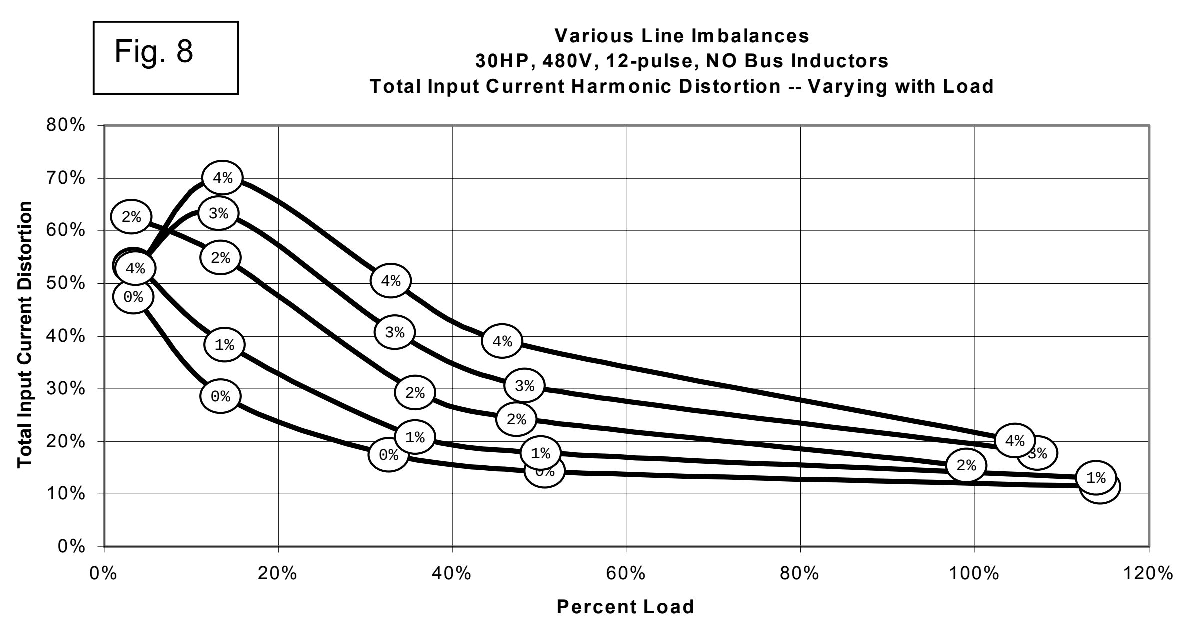


Fig. 8

5 EIGHTEEN PULSE RECTIFIERS

5.1 18-Pulse Rectifier Theory of Operation

Eighteen pulse configurations use a transformer with three sets of three phase outputs that are phase shifted by 20 degrees each, to supply three sets of full wave bridge rectifiers. Theoretically, this configuration cancels the 5th, 7th, 11th, 13th, 23rd, 25th, 29th, 31st, etc harmonics. One might imagine that it may be quite optimistic to expect the nine supply voltages, feeding three bridge rectifiers, to be exactly equal at all operating conditions. Maintaining equal DC current through three bridges seems more difficult than with twelve pulse systems simply because the number of variables increases by fifty percent. As with 12-pulse systems, the 18-pulse rectifier's ability to reduce harmonic currents is best when operating at full load conditions and when all of the nine voltages are equal.

5.2 18-Pulse Rectifier Performance at Full Load with Balanced Line Voltages

In a laboratory exercise it is possible to control the three line voltages that supply the 18-pulse transformer primary winding, however in real life applications this may be quite difficult to achieve. Even when the primary voltages are balanced, maximum attenuation of harmonics with 18-pulse rectifiers, requires that all nine secondary voltages be balanced. This allows DC current to be shared equally by each of the three bridge rectifiers, provided the semiconductor and circuit resistances are identical for all phases. Due to the large number of variables, the likelihood of achieving theoretical harmonic performance is rather poor. *Fig. 9* demonstrates the harmonic current spectrum measurement for an 18-pulse rectifier, operating at full load, with the three primary voltages balanced. To demonstrate the best case scenario, the three bridge rectifiers were connected in series to assure equal sharing of DC current.

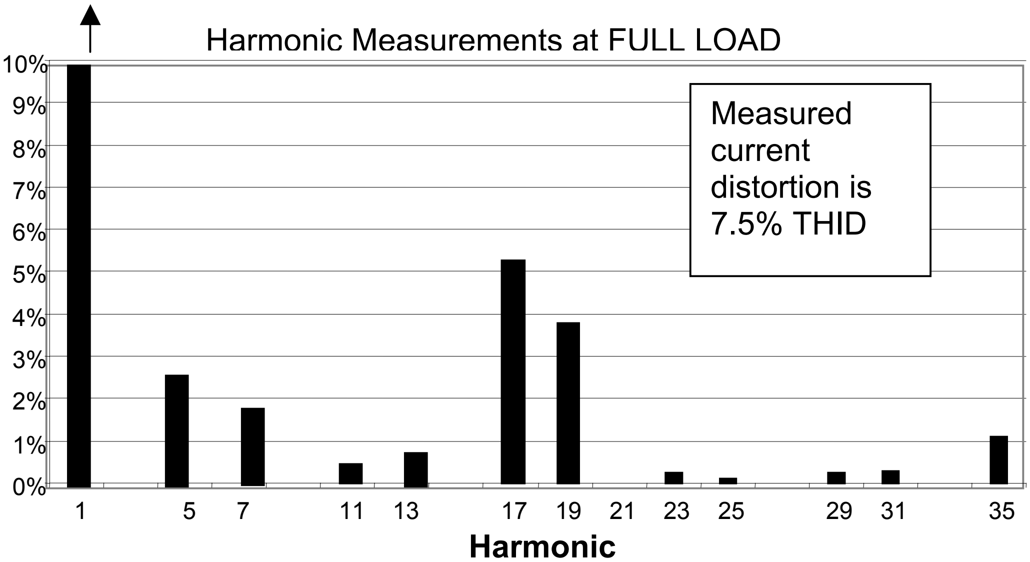


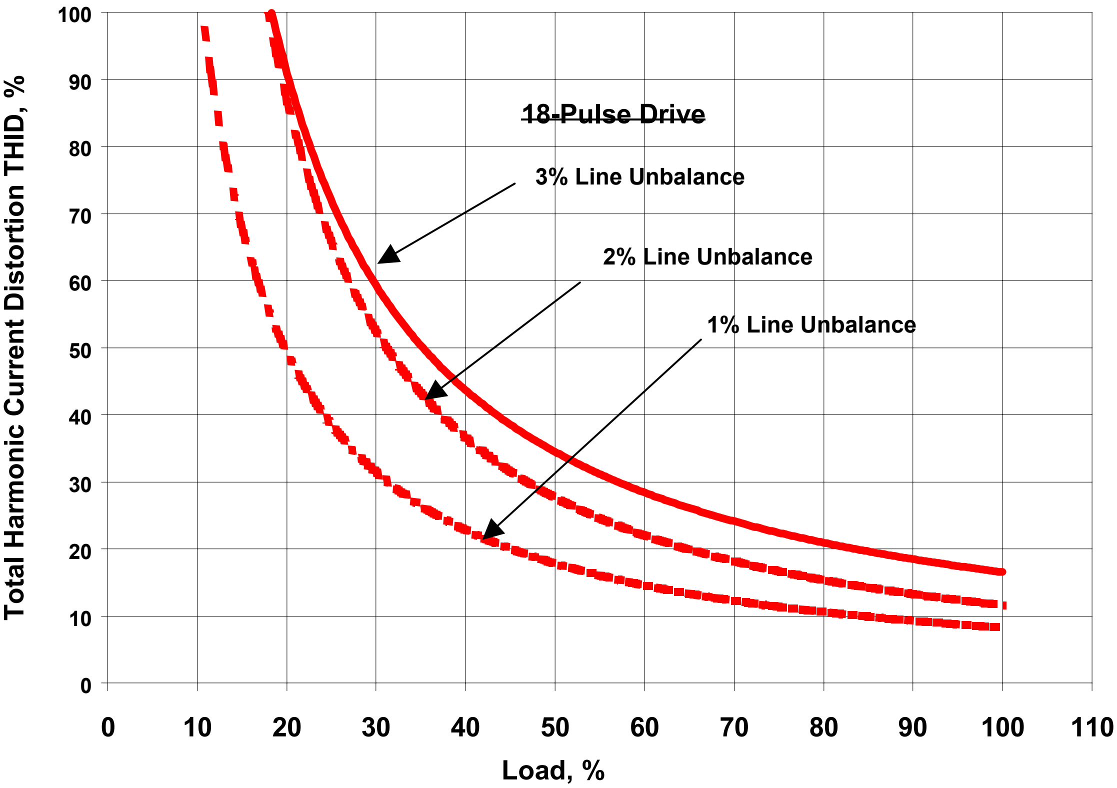
Fig. 9 Harmonic spectrum for 18-pulse rectifier, measured while *operating at full load*, when line voltages were balanced.

5.3 Effects of Unbalanced Line Voltage on 18-pulse Rectifiers

Similar to twelve pulse systems, 18-pulse rectifiers experience diminishing performance when line voltages are not balanced, and when operating at less than full load. 18-pulse drives may offer guaranteed harmonic distortion levels, but typically only at full load and full speed conditions, with voltages that are balanced within one percent. Fig. 10 illustrates the effect of unbalanced line voltages on 18-pulse drives operating between full load and no load conditions.

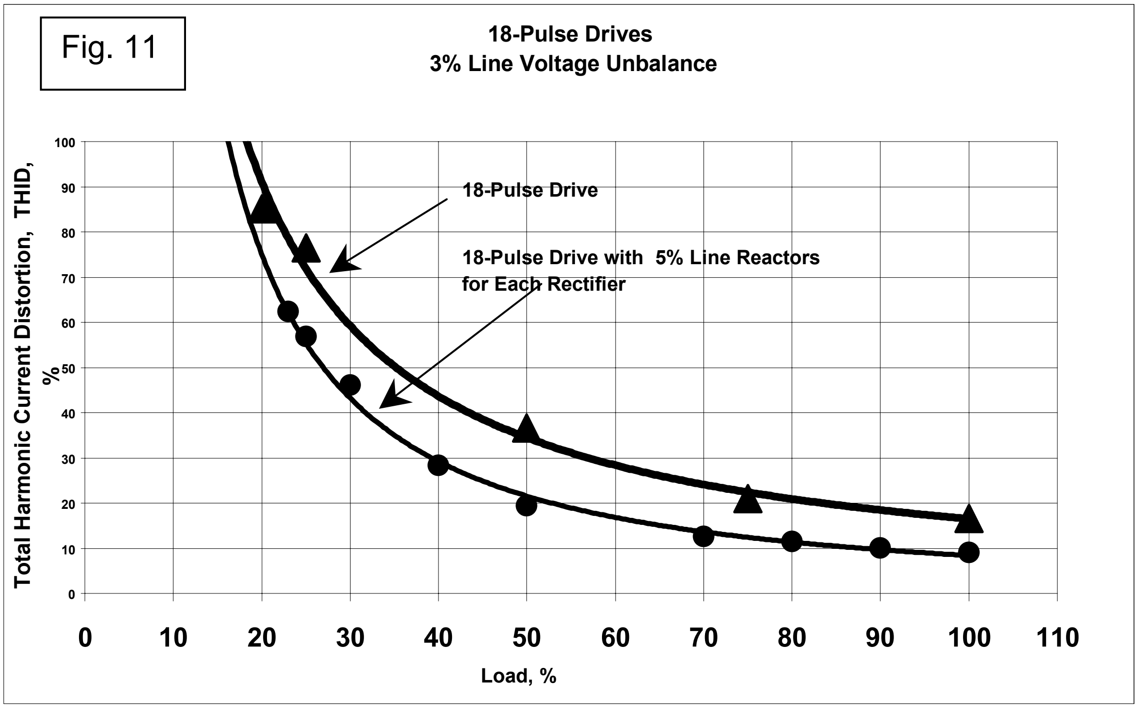
Fig. 10

18 Pulse Drive- with Line Voltages Unbalanced by 1% to 3%



Notice that as the load is decreased the magnitude of percent harmonic distortion increases significantly. While %THID at full load may be fairly low, at 40% load, harmonic current distortion was measured to be over 20%THID, when the line voltages were only one percent unbalanced. When the line voltage unbalance was three percent, the harmonic current distortion increased to over 40%THID. To enhance the performance of 18-pulse drives, line reactors may be added in series with the individual bridge rectifiers. This is demonstrated in *Fig. 11*.

Fig. 11



6 Matrix Harmonic Filters

6.1 Theory of Operation

Matrix Harmonic Filters are low pass, passive harmonic filters. They connect in series at the input to any six pulse drive. Being a low pass filter, the Matrix Filter attenuates each harmonic frequency, resulting in the lowest harmonic distortion levels of any passive filter. Their performance, in real life operating conditions such as unbalanced line voltages and from no load to full load is superior to all of the passive techniques discussed previously in this paper. Typical losses associated with Matrix Harmonic Filters are less than one percent of the load power rating. These low pass filters do not cause power system resonance problems and do not attract harmonics from other non-linear loads sharing the same power source. Harmonic distortion performance guarantees are offered for variable frequency, variable torque applications.

6.2 Matrix Filter Performance

Matrix filters convert any six pulse drive to harmonic mitigation performance that is better than 18-pulse rectification. The typical input current waveform and harmonic spectrum are demonstrated in *Fig. 12(a)* and *Fig. 12(b)*.

Fig. 12(a) Matrix Filter Input Current

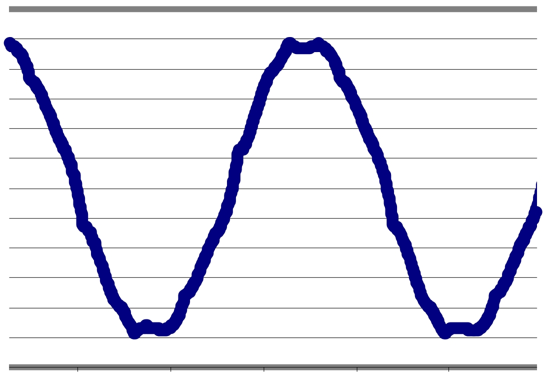
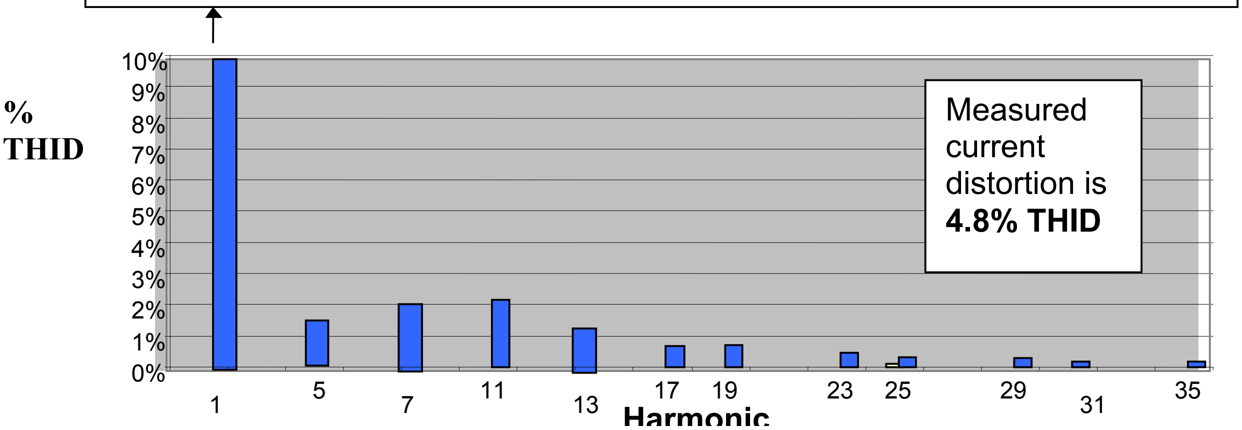


Fig. 12(b) Actual Matrix Filter Harmonic Measurements at FULL LOAD

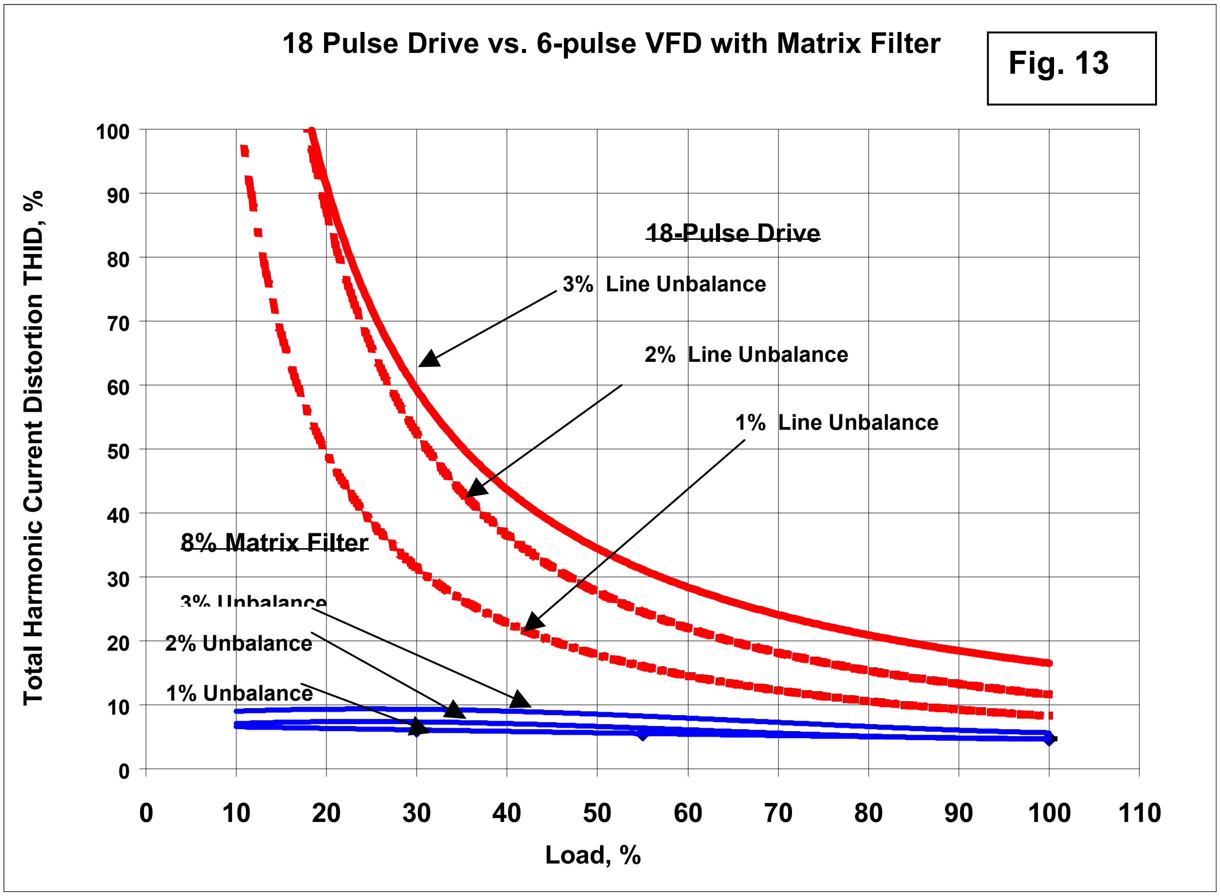


Measured current distortion is **4.8% THID**

Fig. 12(b) Input current spectrum for 6-pulse drive with Matrix Filter.

6.3 Matrix Filter Performance with Unbalanced Line Voltage

Due to their internal series reactance, component tolerances and circuit configuration, Matrix Filters are only mildly affected by unbalanced line voltage conditions. It is also apparent in *Fig. 13*, that Matrix Filter performance is quite consistent from no load to full load conditions. This is demonstrated by the comparison of Matrix Filters to the 18-pulse drives previously discussed. The combination of six pulse VFD and Matrix Filter attenuated harmonics better than the eighteen pulse drive, when tested with various percentages of line voltage unbalance, and when operating at load conditions ranging from 0% to 100% load. By comparison of *Fig. 11* and *Fig. 13*, the six pulse drive with Matrix filter also reduced harmonics to lower levels than the enhanced 18-pulse drive, which used additional line reactors.



7 TRIPLEN HARMONICS

Triplen harmonics are typically not present in a balanced three phase system. They occur however when the line voltages are not balanced, or when the line voltage is distorted by non-linear single phase loads. The presence of triplen harmonics increases the resultant THID level for virtually any passive harmonic mitigation equipment. Some mitigation techniques, such as multi-pulse drives, are highly sensitive to voltage unbalance as demonstrated in *Fig. 8, Fig. 11* and *Fig. 13*. Tuned 5th harmonic traps also experience significantly elevated %THID levels when line voltages are not balanced, as demonstrated in *Fig. 6*. Matrix Filters achieve better attenuation of harmonics under real life operating conditions because they are only minimally influenced by unbalanced line voltages, as demonstrated by *Fig.13*. Additionally, they provide superior harmonic mitigation performance at operating conditions that range from no load to full load.

8 CONCLUSION

Electrical system reliability and normal life expectancy of electrical equipment rely heavily upon a clean and reliable power supply. Those wishing to maximize productivity through utilization of clean power technologies have several harmonic mitigation techniques available. Each technique has a different cost, power loss, and harmonic distortion reduction benefit. Some solutions, such as Matrix Harmonic Filters provide harmonic performance guarantees, while others may require extensive analysis. This paper demonstrates that theoretical performance is not necessarily a valid estimate of the actual expected performance of most mitigation techniques when operating under real life conditions. The performance level of most techniques diminishes in the real world due to the presence of unbalanced line voltages and operation at less than 100% loading conditions.