18-PULSE VFD
VS
LINEATOR / 6-PULSE VFD

TESTING ON
75HP, 480V VFD'S

PERFORMANCE REPORT

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EXECUTIVE SUMMARY

On June 3, 2003 a 75HP, 480V 18-Pulse Variable Frequency Drive (VFD) was tested in the Harmonics and Energy (H&E) Lab at MIRUS International Inc.'s Mississauga, Ontario, Manufacturing Plant. Performance was compared to that of a 6-Pulse VFD (the identical one used for the 18-Pulse model but with its AC line reactor removed) equipped with a 75Hp, 480V LINEATOR™ Universal Harmonic Filter (UHF), Model #UHF-75-480-60-DO.

The LINEATOR™/6-Pulse combination outperformed the 18-Pulse model in essentially all areas with the most impressive being the improvement in system efficiency. The following is a summary of the key performance parameters:

1. The overall system efficiency when running the LINEATOR™/6-Pulse combination was 2% – 3% better than the 18-Pulse VFD over the entire operating range. This offers the customer a substantial savings in energy.
2. Input Current Harmonic Distortion (Ithd) for both systems was essentially the same when the applied 3-phase voltage was well balanced (Ithd = 5% - 6% at full load). However, the performance of the 18-Pulse VFD dropped off dramatically (Ithd = 7.2% at full load) when a voltage imbalance of just 1% was applied. The performance of the LINEATOR™/6-Pulse combination, on the otherhand, remained virtually unaffected by the increased voltage imbalance ensuring that good performance would be achieved in real world applications.
3. At full load, the DC bus voltage of the 18-Pulse VFD was more than 8% lower than nominal. The LINEATOR™/6-Pulse combination, on the other hand, introduced a < 4% DC bus voltage drop at full load preventing high motor currents, overheating and potential motor failures.
4. The LINEATOR™/6-Pulse combination did introduce a slight voltage boost at lightly loaded conditions but the DC bus was kept to within 5% of nominal.
5. The 75HP LINEATOR™ is substantially smaller than the 18-Pulse phase shifting transformer. Combining this with the fact that the 18-Pulse solution requires additional reactors to improve performance and prevent cross-commutation, the LINEATOR™/6-Pulse package could be nearly 1/3 smaller than the 18-Pulse solution.

BACKGROUND

The front-end rectifiers of 3-phase, 6-pulse static power convertors (AC-DC), such as those found in variable frequency drives, are considered non-linear because they draw current in a non-sinusoidal manner. The current harmonics they generate are predominantly the 5th and 7th with 11th, 13th and other higher orders also present but at lower levels.

Power distribution systems that carry a heavy non-linear load component will often experience problems due to excessive harmonic currents. Problems that can arise include:

- Power factor correction capacitor failures
- Overheating cables, transformers and other distribution equipment
- Distortion of the voltage waveform (typically flat-topping) especially when operating on emergency standby generators
- False tripping of circuit breakers
- Premature failure of motors, generators and other rotating equipment
- Misoperation or component failure in PLC's, computers and other sensitive loads

In order to reduce the harmonics generated by variable frequency drives, many drive manufacturers have introduced multi-pulse drive packages. These drive packages integrate various types of phase shifting transformers with multiple bridge rectifiers to induce cancellation of targeted harmonics and lower the current harmonic distortion at the input to the VFD.

12-Pulse VFD's require two rectifier bridges and a dual output transformer with 30° phase shift between the outputs in order to cancel the majority of 5th, 7th, 17th and 19th current harmonics. With a well balanced supply voltage, total harmonic current distortion at full load can be reduced to around 10% - 12%.

In order to reduce current harmonics further, many drive manufacturers offer an 18-Pulse VFD solution similar to the one tested for this report. A three output transformer is used to supply three rectifier bridges in order to cancel 5th, 7th, 11th and 13th harmonics. In well configured 18-pulse systems with well balanced voltages, current harmonic distortion may reach levels as low as 5% at full load. But if the voltages are unbalanced by as little as 1%, performance can drop off dramatically.

One major downfall of multi-pulse VFD's is that the requirement for a phase shifting transformer and additional reactors results in a significant increase in losses and subsequent drop in efficiency. Mirus' LINEATOR™ Universal Harmonic Filter can meet or exceed the performance levels of 18-pulse while maintaining losses and efficiency that are comparable to a VFD with an input line reactor or DC link choke.

The LINEATOR™ is a purely passive device consisting of a revolutionary new reactor combined with a relatively small capacitor bank. Its innovative design achieves cancellation of all the major harmonic currents generated by VFD's and other similar 3-phase, 6-pulse rectifier loads resulting in Ithd of < 8% and often as low as 5%.

Although referred to as a filter, the LINEATOR™ exhibits none of the problems that plague conventional filters, such as:

Attraction of harmonics from other sources: As a parallel connected device, a conventional trap filter has no directional properties. It therefore, can easily be overloaded by attracting harmonics from upstream non-linear loads. *The LINEATOR™, on the other hand, will present a high impedance to line side harmonics eliminating the possibility of inadvertent importation and overloading.*

Potential for system resonance: At frequencies below its tuned frequency, a conventional filter will appear capacitive. This capacitance has the potential of resonating with the power systems natural inductance. When a filter is tuned to a higher order harmonic, such as the 11th, it can easily resonate at a lower harmonic frequency, such as the 5th or 7th. *The natural resonance frequency of the LINEATOR™ is below that of any predominant harmonic, therefore inadvertent resonance is avoided.*

Leading power factor with high capacitive reactance: The large capacitor banks in both trap filters and broadband filters present a capacitive reactance to the system, especially under light loads. This can be a beneficial feature when inductive loads require a compensating reactance to improve a low displacement power factor. However, in many VFD applications, displacement power factor is quite high even though overall power factor is low due to the harmonic content. Compensation for inductive loads is not necessary and, in fact, can cause problems especially when supplied by an emergency standby generator. To address this, more sophisticated filters will be equipped with a mechanism for switching out the capacitors under light loads, increasing cost and complexity. *Even under no load conditions, the capacitive reactance of the LINEATOR™ is so low (kVAR/kVA ratio of <15%) that switching out the capacitors is unnecessary and compatibility with engine generators is assured.*

Poor harmonic distortion reduction: The filtering effectiveness of a trap filter is dependent upon the amount of harmonics present at untuned frequencies as well as the residual at the tuned frequency. To obtain performance better than 15% Ithd, multiple tuned branches are often required. Some broadband filters claim < 12% Ithd but require relatively large capacitor banks to achieve this. Even larger capacitors are required if further reduction in Ithd is desired. *The LINEATOR™ will reduce current demand distortion to < 8% over the entire operating range and typically achieves near 5% Ithd at full load.*

TEST SETUP

The objective of the testing at Mirus' Harmonics & Energy (H&E) Lab was to compare current distortion, efficiency and DC bus voltage levels on both an 18-Pulse VFD and a LINEATOR™/6-Pulse VFD combination. The instruments used for measurement were two Power Measurement Ltd., ION 7500 revenue class 0.2 digital power meters synchronized to measure concurrently. The ION 7500 has 0.1% accuracy on power measurements and measures harmonics up to the 63rd. A Fluke 41B harmonics analyzer was also used for some harmonics measurements and waveform and spectrum captures.

The 18-Pulse VFD tested was a 75HP, 480V, 60Hz autotransformer configuration equipped with interphasing reactors to prevent cross-commutation. In order to ensure a fair comparison, the LINEATOR™ tests were performed with the identical 75HP VFD used in the 18-Pulse configuration. The LINEATOR™ was added after removing the phase shifting transformer, associated reactors, including the AC line reactor in the VFD, and the extra rectifier bridges. All other components, required for by-pass and other options, were left in the circuit.

Loading of the VFD was accomplished by using 2 x 100HP induction motors coupled together. The second motor was connected to the power grid to operate as a generator as the frequency of the VFD was adjusted away from 60Hz.

Efficiency calculations were made by taking the ratio of the kW power delivered back into the power system by the MG set to the kW power drawn at the input to the phase shifting transformer of the 18-Pulse VFD or the input to the LINEATOR™ filter. The ratio was averaged over several seconds in order to ensure better accuracy of measurement. This 'system efficiency' measurement, of course, is much lower than the efficiency of the VFD itself because of the added losses of the MG set. Overall system efficiency was used rather than simple VFD efficiency because of the difficulty in accurately measuring the PWM output of the VFD.

Current and voltage distortion measurements were taken at the input to the 18-Pulse phase shifting transformer and the LINEATOR™ filter. DC bus voltage was measured directly from the DC bus of the VFD.

During testing, the 3-phase applied voltage as supplied by the Utility was quite well balanced (< 0.2%). Since it is commonly known in the industry that multi-pulse systems lose some of their effectiveness in canceling harmonics as the applied voltage becomes imbalanced, tests were repeated with the applied voltage imbalance increased to 1%.

PERFORMANCE MEASUREMENTS

<u>18-Pulse VFD Test Results:</u>

Figure 1 below is a snapshot of the measurements displayed by the ION 7500 metering software taken with the 18-Pulse VFD running at full load. Table 1 provides the measurements at various load levels.

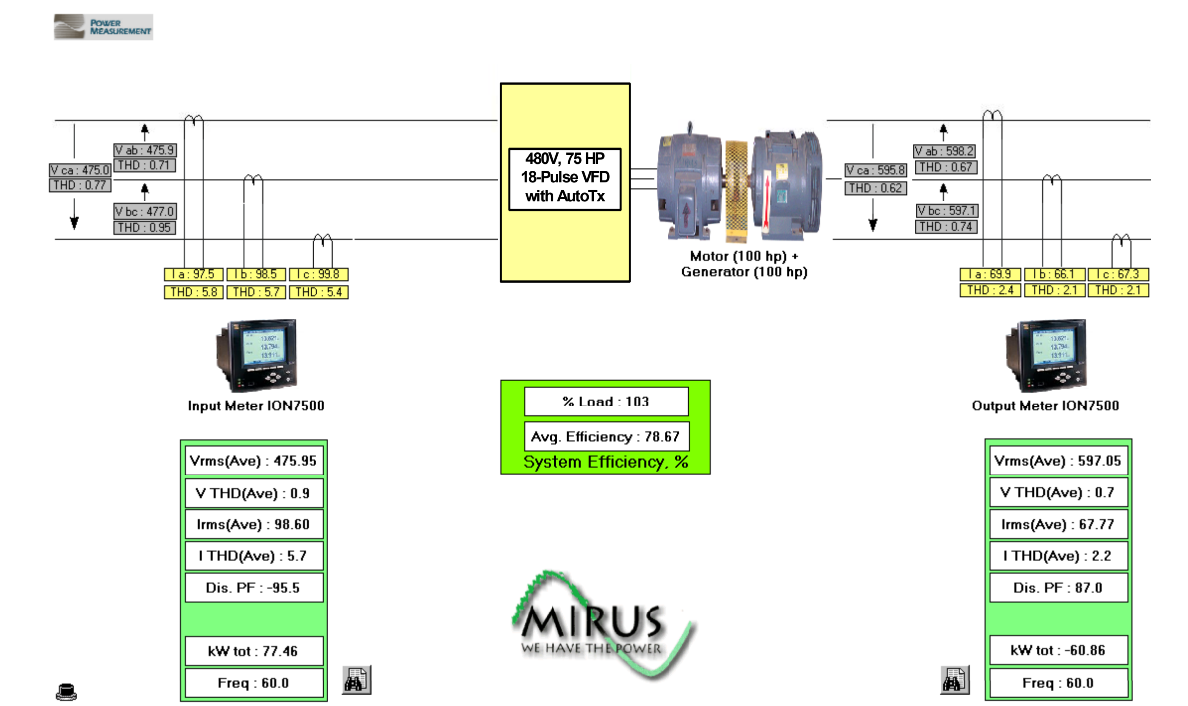

Figure 1: ION 7500 measurements for 75HP, 480V 18-Pulse VFD at full load

%Load	Vrms(ave)	Irms(ave)	ITHD (%)	System Efficiency	DCBus(V)	Normalized DCBus(V)
103	475	96.9	5.7	78.7	607	91.3
93	476	85.3	5.6	80.6	614	92.2
83	476	75.0	5.7	81.3	619	93.0
73	476	64.9	5.9	81.9	623	93.5
63	478	55.0	5.8	82.7	630	94.2
51	478	45.3	6.6	81.6	638	95.4
40	477	35.6	7.2	80.4	644	96.4
27	479	25.4	7.9	79.7	650	97.0
13	479	14.4	10.6	69.2	658	98.2
0	478	2.5	38.1	0.0	672	100.3

Table 1: ION 7500 measurements for 75HP, 480V 18-Pulse VFD at various load levels

Figure 2 below shows the measurements taken with the 18-Pulse VFD running at full load but with voltage imbalance of 1%. Table 2 provides the measurements at various load levels.

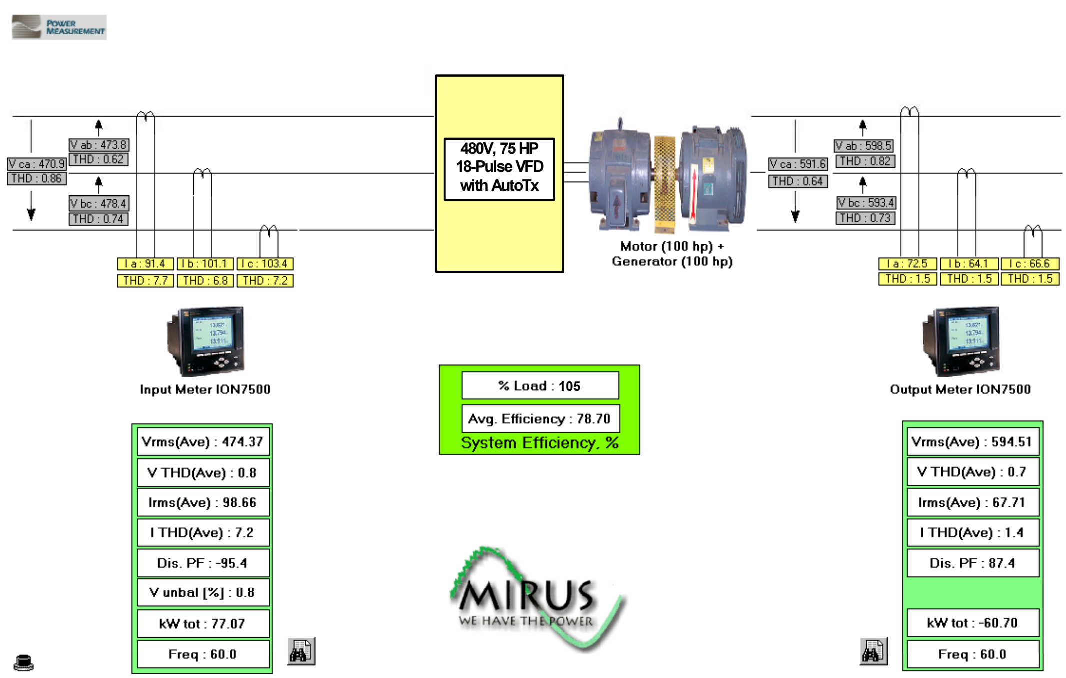

Figure 2: ION 7500 measurements for 75HP, 480V 18-Pulse VFD at full load and 1% voltage imbalance

%Load	Vrms(ave)	Irms(ave)	ITHD (%)	System Efficiency	DCBus(V)	Normalized DCBus(V)
105	474	98.7	7.2	78.7	618	93.1
92	474	85.0	7.2	80.2	622	93.7
85	475	77.0	7.8	81.3	625	94.1
74	475	65.9	8.3	82.5	627	94.2
58	475	51.5	9.8	83.4	633	95.2
54	475	47.9	10.4	82.6	640	96.3
36	476	32.8	15.7	80.5	644	96.7
21	476	20.8	19.4	75.0	648	97.3
18	476	18.8	21.5	72.6	658	98.8
0	476	2.5	40	0.0	672	100.8

Table 2: ION 7500 measurements for 75HP, 480V 18-Pulse VFD at various load levels and 1% voltage imbalance

LINEATOR™/6-Pulse Test Results:

Figure 3 below is a snapshot of the measurements displayed by the ION 7500 metering software taken with the LINEATOR™/6-Pulse combination running at full load. Table 3 provides the measurements at various load levels.

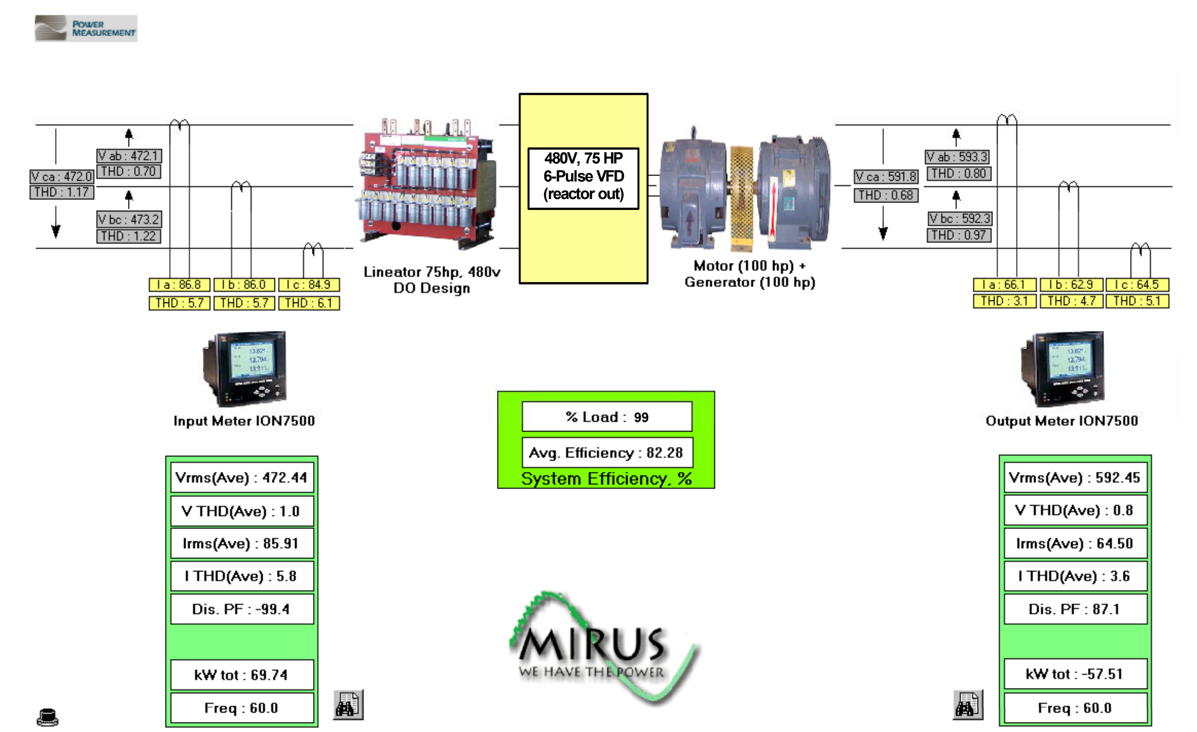

Figure 3: ION 7500 measurements for 75HP, 480V LINEATOR™/6-Pulse combination at full load

%Load	Vrms(ave)	Irms(ave)	ITHD (%)	System Efficiency	DCBus(V)	Normalized DCBus(V)
108	472	96.6	6	81.3	623	94.3
99	472	85.9	5.8	82.3	635	96.0
88	472	75.0	5.5	83.3	646	97.8
77	471	65.5	6.1	84.0	653	99.1
64	469	55.0	7.6	84.8	658	100.2
52	473	45.0	8	84.5	665	100.5
38	471	35.1	9.5	82.7	668	101.3
25	471	25.7	10.2	81.5	670	101.6
9	472	15.4	10.8	71.0	673	101.9
0	474	10.0	12.1	0.0	698	105.2

Table 3: ION 7500 measurements for 75HP, 480V LINEATOR™/6-Pulse combination at various load levels

Figure 4 below shows the measurements taken with the LINEATOR™/6-Pulse combination running at full load but with voltage imbalance of 1%. Table 4 provides the measurements at various load levels.

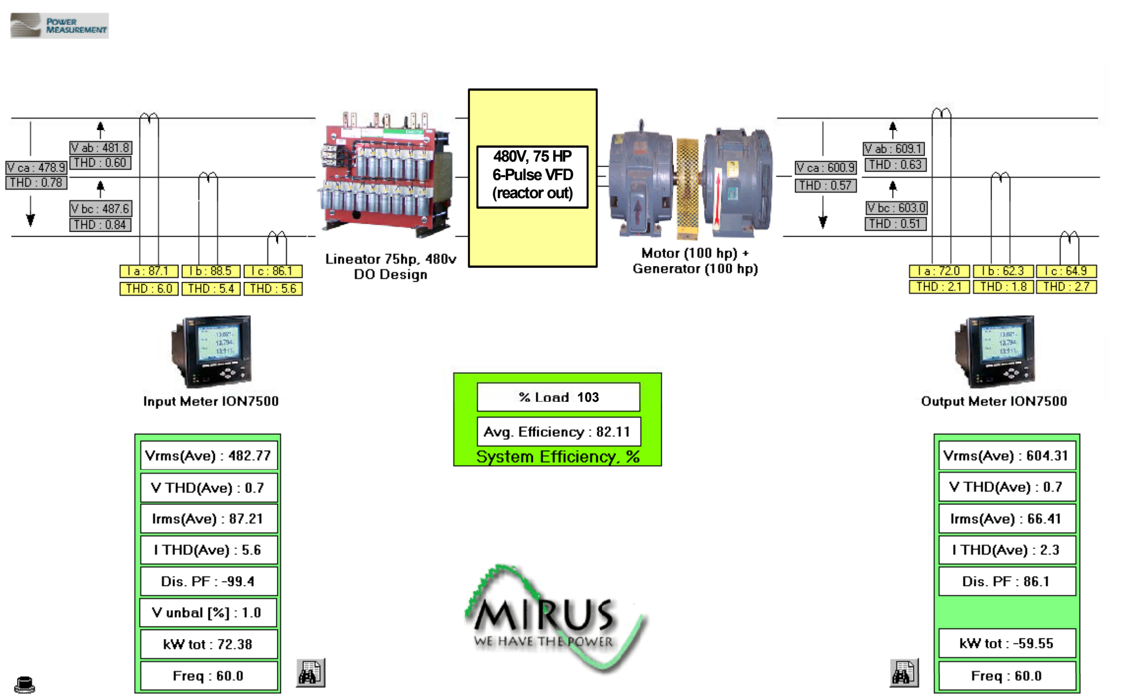

Figure 4: ION 7500 measurements for 75HP, 480V LINEATOR™/6-Pulse combination at full load and 1% voltage imbalance

%Load	Vrms(ave)	Irms(ave)	ITHD (%)	System Efficiency	DCBus(V)	Normalized DCBus(V)
111	482	97.1	6.1	80.8	637	94.3
103	483	87.2	5.6	82.1	652	96.5
90	483	75.1	6.2	83.3	663	98.0
75	483	62.3	6.3	84.3	672	99.4
65	484	54.0	7	84.6	677	99.9
56	484	47.2	7.7	83.2	680	100.4
38	481	34.5	9.2	81.6	686	101.9
25	481	26.0	10.6	72.9	690	102.4
11	481	16.9	10.8	59.3	692	102.8
0	482	10.2	12.8	0.0	722.5	107.1

Table 4: ION 7500 measurements for 75HP, 480V LINEATOR™/6-Pulse combination at various load levels and 1% voltage imbalance

OBSERVATIONS AND CONCLUSIONS

Although the 18-Pulse VFD solution and the LINEATOR™/6-Pulse combination compared favourably with respect to their ability to reduce input current distortion under balanced voltage conditions, the LINEATOR™/6-Pulse combination outperformed the 18-Pulse in many other areas.

Figure 5 shows the current distortion measurements with both well balanced and 1% imbalanced supply voltages. The LINEATOR™/6-Pulse maintained its excellent performance even with the voltage imbalance of 1%. The 18-Pulse solution had very good performance with a well balanced 3-phase supply but was much less effective with the higher voltage imbalance. Since a slight voltage imbalance is not unusual, the 18-Pulse solution will not always be able to guarantee good performance.

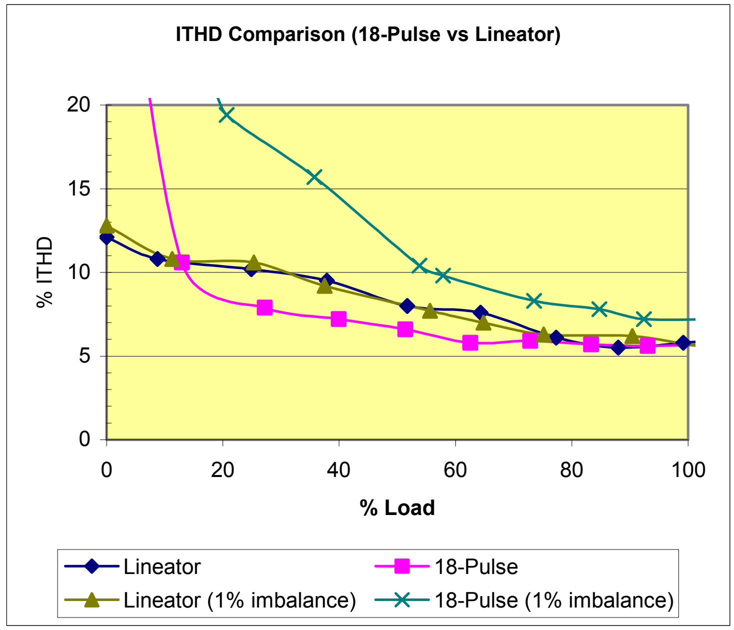

Figure 5: Input Current Distortion comparison – 18-Pulse vs LINEATOR™/6-Pulse combination

The advantages of the LINEATOR™/6-Pulse are even more evident when a comparison of system efficiencies is observed. The LINEATOR™ /6-Pulse combination achieved efficiencies that were 2% - 3% points higher than the 18-Pulse across the entire operating range. This would translate into very substantial energy savings and an improved payback for the installation.

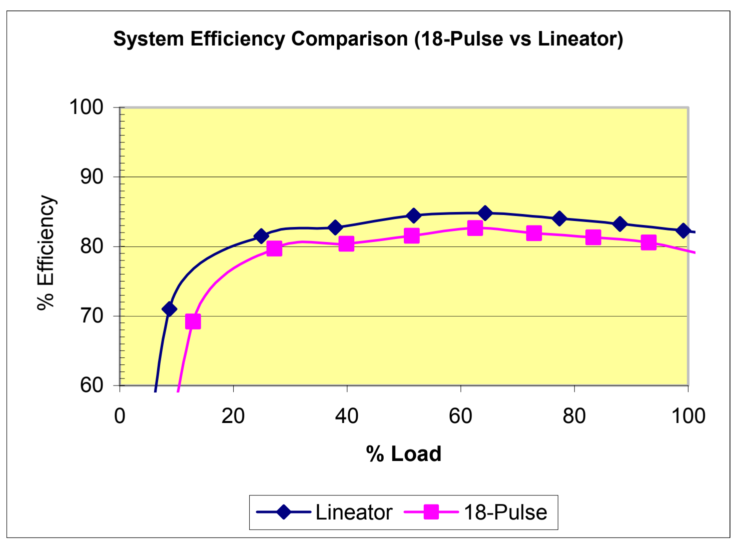

Figure 6: System efficiency comparison – 18-Pulse vs LINEATOR™/6-Pulse combination

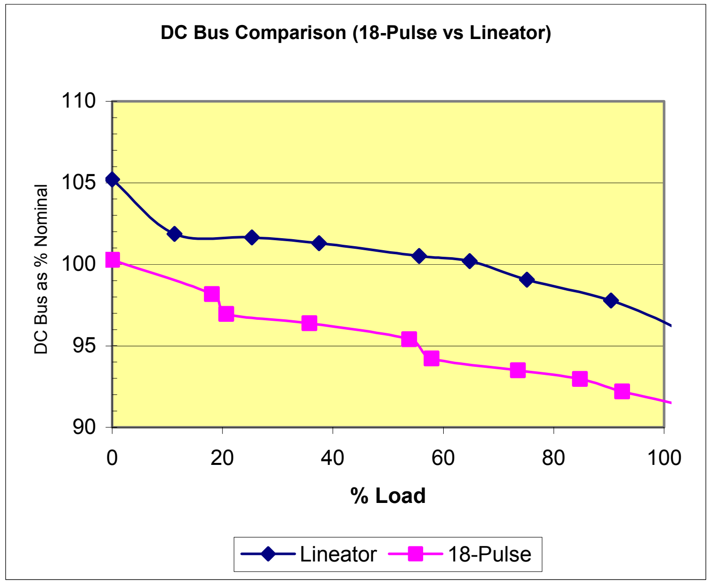

Figure 7: DC Bus Voltage comparison – 18-Pulse vs LINEATOR™/6-Pulse combination

The DC bus voltage level of the VFD is another interesting comparison. At light loads, the capacitors within the LINEATOR™ tend to boost the VFD's DC bus voltage slightly. The unique reactor design of the LINEATOR™ allows it to achieve its excellent performance while minimizing this voltage boost to 5% or less.

What is arguably more important is the DC bus voltage drop at full load. Any impedance added to reduce input current distortion will introduce a voltage drop as the VFD is loaded. Even a 5% AC line reactor will reduce the DC bus voltage by about 5% at full load. As the voltage drops, the motor will have to draw more current in order to deliver the power required for the application. As current increases the losses in the motor will increase proportional to the square of this current. The motor will run much hotter and could be susceptible to overheating and pre-mature failure.

As shown in Figure 7, the 18-Pulse VFD introduced more than an 8% DC bus voltage drop at full load. This is due to the fact that the 18-Pulse solution requires significantly more impedance to reach the performance level of the LINEATOR™. The total impedance includes the phase shifting transformer, reactors to prevent cross-commutation, an AC line reactor ahead of the phase shifting transformer and the AC line reactor within the VFD itself. The impedance of the LINEATOR™ is a combination of the reactor and capacitors resulting in much lower through impedance presented to the VFD. The high number of inductive components in the 18-Pulse VFD also explains why the losses are much higher and efficiency lower.