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VFD Input Harmonic Performance

Recently, the dated use of pulse count as an indicator of harmonic performance has led to misrepresentation of actual harmonic distortion and the impact of those harmonics to a VFD user's plant power grid. The premillennial idea that simply increasing the pulse count leads to better harmonic performance is no longer true as the selected topology plays an important role in actual harmonic generation and distortion.

While low voltage VFD technology has settled on a single configuration there are many different topologies used by manufacturers of medium voltages VFD's; current source, voltage source, passive front end, active front end, etc. They vary in both rectification method and inverter design. Two of the main MV topologies in the industry are used in designs that are manufactured by Siemens, the Cascaded H Bridge design utilized in the GH180 Perfect Harmony and the 3/5 level Neutral Point Clamp design utilized by the Sinamics GM150. Both designs have different methods for power rectification with the Sinamics using the more traditional method common in the early days of rectification starting in the 1950's and the Perfect Harmony using a newer (since 1994) design. This paper focuses on the differences between these designs and the harmonic distortion created at the input of the VFD as well as the Point of Common Coupling (PCC) by both rectifier topologies.

Industry Standard Definition

One of the oldest industry standard MV VFD designs is commonly referred to as the Phase Controlled Rectifier (PCR) using Thyristors (Silicon controlled rectifiers, SCR) but 6-pulse diode rectifiers are also used in 6, 12 or 18 pulse configurations. The PCR utilized an input isolation transformer with 3 phase shifted secondary windings configured to feed three rectifiers. The phase shifted secondary windings create a "standard" 18 pulse arrangement at the primary of the isolation transformer as shown in Figure 1.

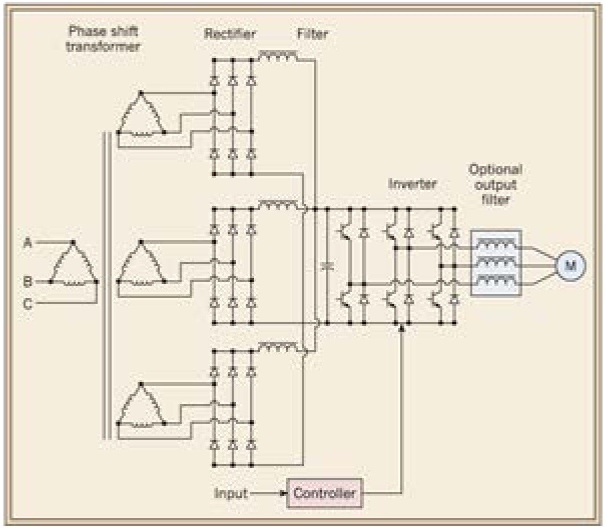


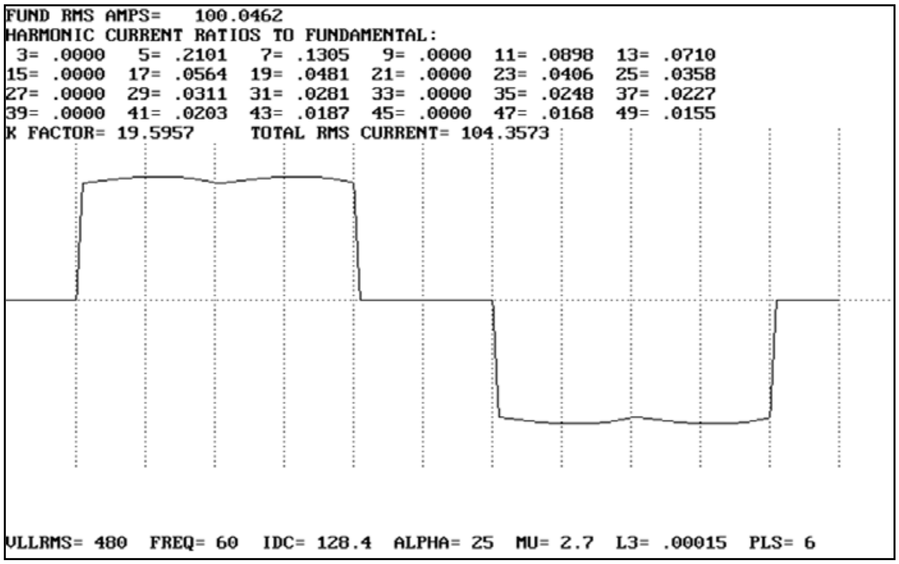
Figure 1 Typical 18-Pulse Rectifier

Multipulse rectifiers achieve harmonic reduction by cancellation of harmonics. The harmonics of an individual rectifier are unchanged, but when you phase shift the voltage, the harmonic currents are shifted by (harmonic number * fundamental phase shift). The phase shifts are chosen so that the harmonic currents in the individual rectifiers cancel in the transformer. However, in addition to the phase shifts, the voltages must also match very closely. That is, the MMF's of these harmonic currents add to zero so they do not appear in the primary current.

The traditional design for an 18 pulse input usually cannot meet IEEE519 requirements for harmonic mitigation as it included notching of the input waveform requiring the addition of input filters (and power factor correction in the case of PCR). For this reason some specifications only allow 24-pulse rectifier circuits as a minimum, assuming this meets IEEE519 which is not necessarily true. As we shall see, the rectifier topology and connections influence the true harmonic distortion performance and even a 24-pulse rectifier arrangement in some topologies cannot meet IEEE519 harmonic limits.

Why is there a difference in two systems that both publish the fact that they use an 18-pulse rectifier? The short answer is that the configuration of the rectifier and its connections influence the actual harmonics it produces. So not all 18-pulse systems are equal and for that matter, depending on the rectifier circuit some 18-pulse rectifier systems may out perform a 24-pulse system! The reason behind this is primarily a function of the circuit connections which in turn cause fast rising current waveforms.

The time rate of change (di/dt) of the current into the rectifiers is very important in determining the harmonic spectrum, especially at the higher harmonics. Slower rates of change of current suppress the higher harmonics. Thyristor converters and diode rectifiers in series tend to have steep sided quasi-square wave currents as shown in Figure 2. Any rectifier feeding an inductance will have this waveform. It is worth noting that VFD's with series rectifiers (GH150, GM150 and other NPC units) feeding a common DC link capacitor will have significantly worse harmonic performance (for the same pulse number) than the GH180 Perfect Harmony in which the rectifiers are not in series.



```
FUND RMS AMPS=   100.0462
HARMONIC CURRENT RATIOS TO FUNDAMENTAL:
 3= .0000   5= .2101   7= .1305   9= .0000  11= .0898  13= .0710
15= .0000  17= .0564  19= .0481  21= .0000  23= .0406  25= .0358
27= .0000  29= .0311  31= .0281  33= .0000  35= .0248  37= .0227
39= .0000  41= .0203  43= .0187  45= .0000  47= .0168  49= .0155
K FACTOR= 19.5957     TOTAL RMS CURRENT= 104.3573

VLLRMS= 480  FREQ= 60  IDC= 128.4  ALPHA= 25  MU= 2.7  L3= .00015  PLS= 6
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Figure 2 6-Pulse Thyristor Converter Input Current Waveform

Rectifiers driving into individual capacitive loads and diode bridges in parallel (like the GH180 Perfect Harmony) will have slowly rising and falling currents, which provides significantly higher harmonic suppression. From Figure 2, the Total Harmonic Distortion is approximately 40% which is well above the 5% IEEE519 standards.

The characteristic harmonics of the 6-p rectifier are odd harmonics where the harmonic number is pulse number x (N +/- 1), where N is an integer. The significance of the 1/h factor is that a steep sided square wave with a flat top has 1/h as the harmonic value. So the amplitude of the harmonics comes down as the frequency increases. That means the lowest harmonic is the largest, so it becomes the most significant one to deal with. As one can see from the table below, this isn't close to meeting the most stringent IEEE519 limit with the THD at 30% versus an IEEE519 limit of 5%.

N	**Pulse Number x (N – 1)**	**Pulse Number x (N + 1)**	**1/h**	**IEEE519 Limit**
1	5	7	0.2, 0.143	0.04
2	11	13	0.091, 0.077	0.02
3	17	19	0.059, 0.053	0.015
4	23	25	0.043, 0.04	0.006
5	29	31	0.034, 0.032	0.003
6	35	37	0.029, 0.027	0.003
7	41	43	0.024, 0.023	0.003
8	47	49	0.021, 0.02	0.003
		THD	**0.30**	**0.05**

Now if we use two 6-pulse rectifiers as shown in Figure 3 with a 30 degree phase shift an interesting thing happens: some of the pairs of harmonics are cancelled (add to zero) in the transformer and our table becomes:

N	**Pulse Number x (N – 1)**	**Pulse Number x (N + 1)**	**1/h**	**IEEE519 Limit**
1	11	13	0.091, 0.077	0.02
2	23	25	0.043, 0.04	0.006
3	35	37	0.029, 0.027	0.003
4	47	49	0.021, 0.02	0.003
		THD	**0.142**	**0.05**

Using a 12-pulse configuration, we have managed to cancel some of the lower order harmonics but the THD still exceeds the industry limits at 14.2%.

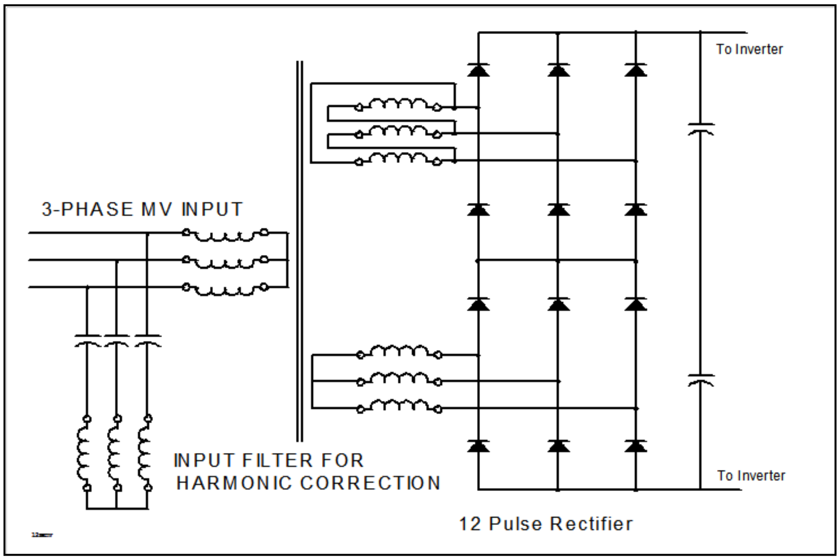


Figure 3 12-pulse Rectifier Arrangement

Further improvement is obtained by using three rectifiers in an 18-pulse arrangement. Increasing the pulse number from 12 to 18 gives more improvement, since it largely eliminates the pairs centered on 6*N and 12*N. Thus 5th, 7th, 11th and 13th harmonics which are the largest are gone. This requires a -20°, 0°, +20° phase shift. The shift is always 60°/m where m is the number of rectifiers. Our table now becomes:

N	Pulse Number x (N – 1)	Pulse Number x (N + 1)	1/h	IEEE519 Limit
1	17	19	0.059, 0.053	0.015
2	35	37	0.029, 0.027	0.003
3	53	55	0.019, 0.018	-
		THD	**0.092**	**0.05**

From the table an 18-pulse system still yields a THD of 9.2% which is almost double the IEEE519 standard. If we continue our progression to a standard 24-pulse rectifier circuit which is typically used today, the belief is that this will meet IEEE519 limitations. A simple measurement of an actual system using a 24-pulse rectifier connected in series and driving a common DC link capacitor identical to the rectifier circuits used on NPC topologies today can be made and the results shown below indicate that this rectifier circuit may also struggle to meet the industry standard limits. Our harmonics become:

N	Pulse Number x (N – 1)	Pulse Number x (N + 1)	1/h	IEEE519 Limit
1	23	25	0.043, 0.04	0.006
2	47	49	0.021, 0.02	0.003
		THD	**0.066**	**0.05**

The 24-pulse fast-rising rectifier arrangement is close to meeting IEEE519 as far as the total ITHD, but the individual harmonics are still outside the acceptable harmonic limits of IEEE519 where the higher order harmonics are the problem. An actual waveform in Figure 4 which shows the significant slope diminishes the higher order harmonics.

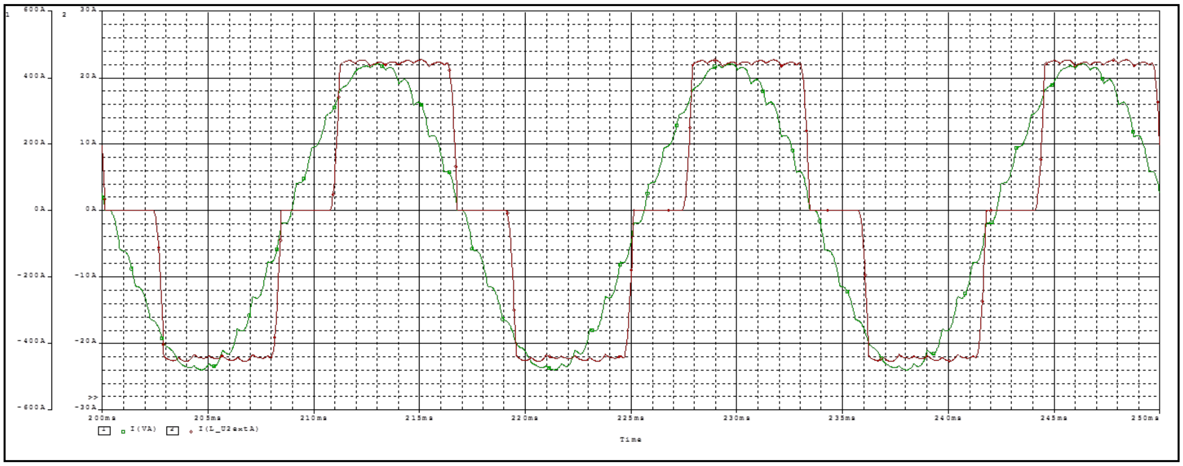


Figure 4 Actual 24-Pulse Currents for Series Rectifiers

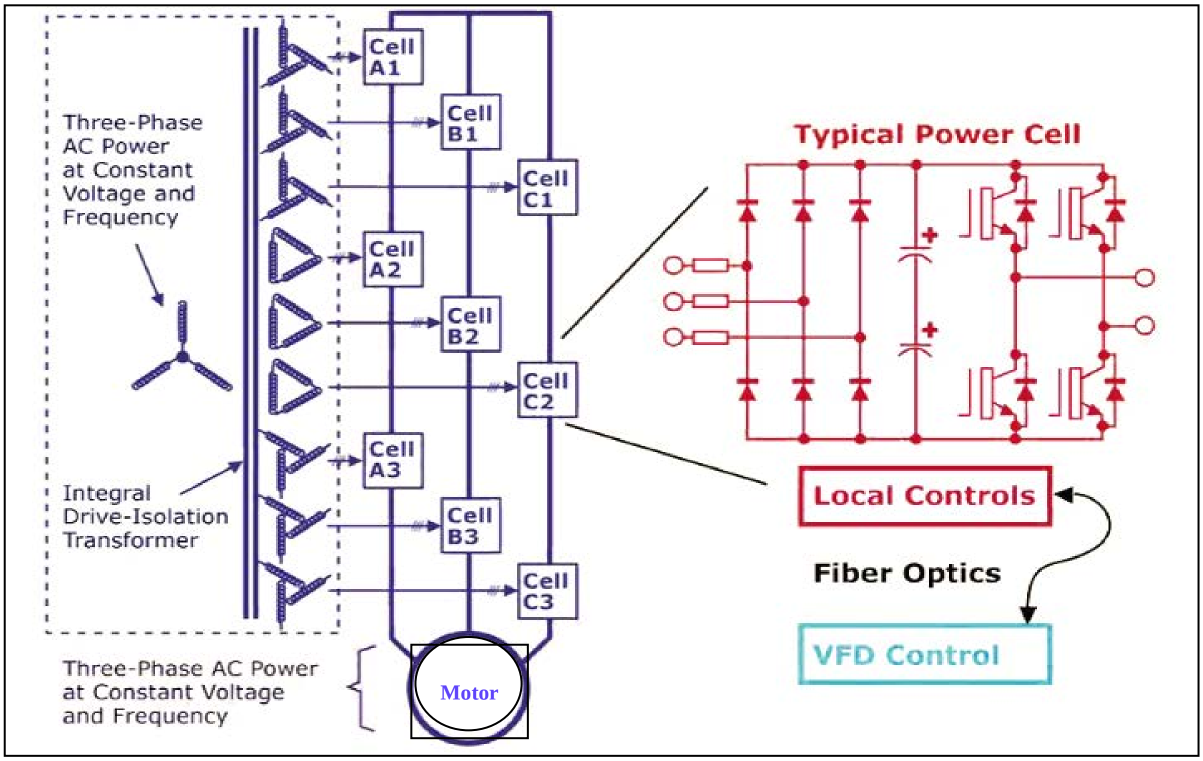
The primary current in green is for a 275kW GH150 drive with 24-pulse input. The red waveform is the current from one transformer secondary phase into the rectifier. The rectifiers are in series causing a relatively high di/dt. The total ITHD is 3.46%; the largest single component is the 23rd harmonic at 2.47%. Although well below the 1/h value, it does not meet the 519 limit. This is a real transformer which has a secondary-secondary impedance of less than 2%, which causes the di/dt to be large, giving substantial high order harmonics.

The standard MV VFD design commonly referred to as the 3 or 5 level Neutral Point Clamp utilizes an input isolation transformer with multiple phase shifted secondary windings configured to feed 6-pulse, full wave diode rectifiers. The phase shifted secondary windings are made of both delta and extended delta windings or two parallel transformers with delta/Wye secondaries which create a standard 24 pulse style rectifier input. This design is the medium voltage VFD industry standard and is used by most manufacturers who utilize a 24 pulse input. This 24 pulse design can inherently meet IEEE 519:1992 harmonic distortion standards (but a Phase controlled rectifier version could still not meet standards). Local power utility standards need to be investigated on a case by case basis to ensure compliance, but generally those standards are met as well. Please note that the telephone interference levels differ between power utility company and compliance to such standards requires analysis.

Perfect Harmony

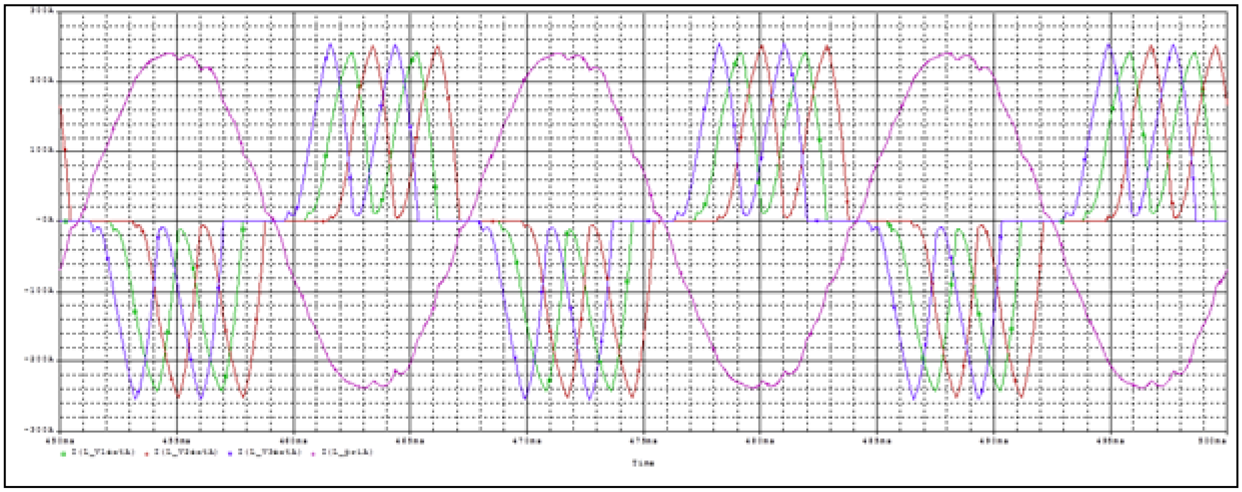
The Siemens GH180 Perfect Harmony design was and is unique to the concept of rectification due to its overall design. It utilizes an input isolation transformer with multiple (minimum 3) phase shifted secondary windings *per phase* each feeding a power module/cell which contains a 6 pulse full wave diode rectifier. The secondary windings in this design are extended delta to maximize the harmonic cancellation and provide the phase shifting required.

The number of power modules installed in a particular Perfect Harmony depends upon the generation of VFD and the output operating voltage. For example the newest designs utilize three power modules/cells per phase to create the necessary 4160V output voltage as shown below. This topology results in a hybrid multi-pulse design for the overall rectifier that does not conform to the old 18/24/30 pulse definitions. The multiple secondary windings that feed each rectifier are divided between the multiple power modules/cells and interact with each other to cancel harmonics within the isolation transformer. The equivalent circuit is more extensive than the industry standard 18 pulse designs, thereby giving it better harmonic distortion performance. Due to the transformer design as described above the harmonic distortion created by a minimum 3 cell per phase hybrid multi-pulse Perfect Harmony is comparable to the industry standard 24 pulse design and rarely requires input filters, meeting IEEE519 “out of the box”.



This modular topology can expand to maximum 8 cells/windings per phase creating an input harmonic impact between what would be a traditional 48 to 54 pulse design, essentially a linear element in the power system with no measurable harmonic distortion.

It was shown that a 24-pulse, series rectifier circuit yielded an overall THD of 3.46% but higher harmonics exceeded the IEEE519 limits. Evaluating the 18-pulse Perfect Harmony topology using **parallel** rectifier circuits feeding their own individual DC link capacitor provides a superior approach to harmonic mitigation. In the case of the Perfect harmony 18-pulse arrangement a typical waveform is shown in Figure 6.



<u>**Figure 6 Perfect Harmony 18-Pulse waveforms**</u>

The primary current is shown in magenta for a 1500Hp Harmony drive with 18-p input. The red, green, and blue waveforms are the secondary currents from the middle group of secondaries. They are severely distorted with 5th and 7th harmonics, but those cancel almost completely. The total ITHD is 3.28% which is slightly less than a 24-pulse conventional rectifier and the largest single component is residual 5th harmonic at 2.26%. This is well below the 5% ITHD limit of IEEE-519. For specific harmonics, the 17th harmonic at 1.43% and the 23rd and 25th harmonics are well below the 0.6% limit.

This indicates that an 18-pulse Perfect harmony rectifier arrangement provides a better harmonic performance than the 24-pulse traditional NPC rectifier arrangements.

When the GH180 Perfect Harmony system configured as a 24-pulse, parallel rectifier arrangement is evaluated as shown in Figure 7, the actual harmonic performance continues to improve.

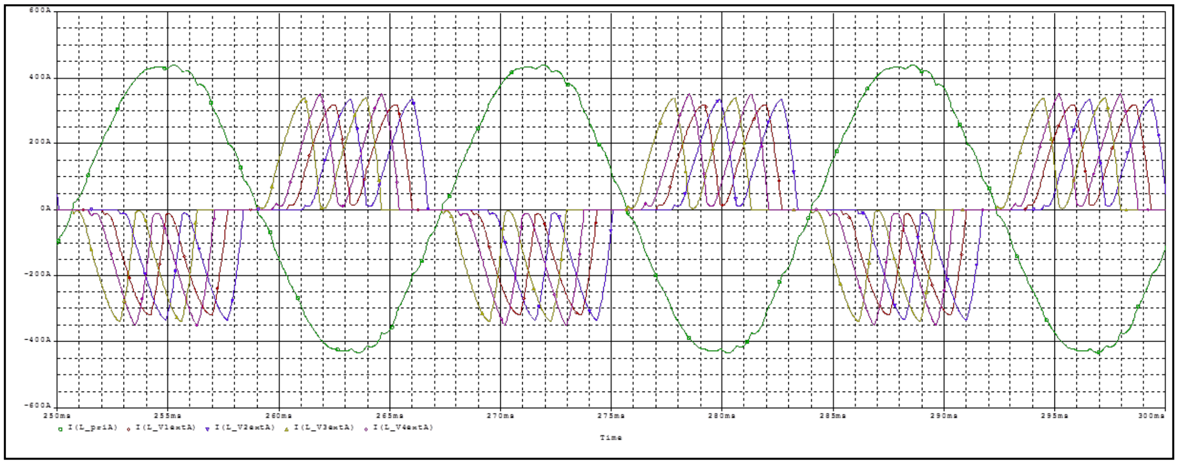


Figure 7 Perfect Harmony 24-Pulse waveforms

The primary current in green is for a 2750Hp Perfect Harmony drive with 24-p input. The cell input currents of the four central windings are also shown with the rectifiers effectively in parallel. The total ITHD is 2.47%; the largest single component is residual 5th at 1.89%. This is well below the 5% ITHD limit of IEEE-519. The ITHD for the 24-pulse is less, 2.47%, than that of the 18-pulse, 3.28%, but they both meet the 5% ITHD. When the distortion levels are this low, there's no practical difference. But the 24-pulse arrangement has more components and decreases other operational specifications such as efficiency, MTBF, etc. and should be evaluated based on the entire drive system.

An actual Harmonic Performance Case Study

A harmonic prediction has been carried using all the design options described above being the industry standard 24 pulse and the Perfect Harmony hybrid front end.

The limits as described in IEEE 519:1992 were utilized as the basis for the prediction. Because of the low harmonic content of the Perfect Harmony design telephone interference levels are achievable if proper investigation is completed to ensure compliance.

During the prediction the following utility and design data was utilized:

- Utility short circuit level was calculated as 287MVAsc.
- 2 x 1000hp VFD's and motors

Please note that the software utilized, ETAP version 11.0, does not allow for accurate modeling of the VFD's being used. As a result the model utilized is the closest the software would allow, but it does give a very close representation of VFD harmonic performance. The transformer configuration for the Perfect Harmony VFD's was made Wye/Delta because all secondary windings are delta wound. The prediction single line and input data used are shown in Figure 8.

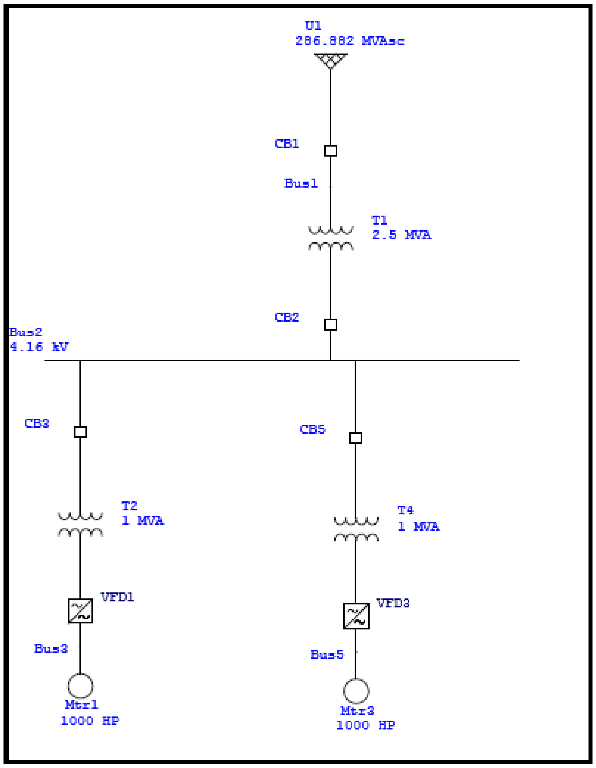


Figure 8 ETAP Single Line

Bus Input data

Bus		% Limits	
ID	**kV**	**VTHD**	**VIHD**
Bus 1	25	5	3
Bus 2	4.16	5	3
Bus 3	4.16	5	3
Bus 5	4.16	5	3

2 Winding Transformer Input Data

Transformer	Rating					
ID	**Primary kV**	**MVA**	**Secondary kV**	**%Z**	**Type**	**X/R**
T1	25	2.5	4.16	7.0	Delta/Wye	10.67
T2	4.16	1.0	4.16	10	Wye/Delta	5.79
T4	4.16	1.0	4.16	10	Wye/Delta	5.79

Harmonics Library

Current Harmonic Source in %

Spectrum order Siemens Perfect Harmony Hybrid multi-pulse

Order	2	3	4	5	6	7	8	9	10	11	12	13	14	15	17	19	23
	25	29	31	35	37	41	43	47	49	53	55	59	61	65	67	71	73
Per unit value	0	0	0	1.19	0	0.30	0	0	0	0.21	0	0.21	0	0	0.24	0.24	0.18
	0.18	0.04	0.04	0	0	0	0	0.02	0.02	0	0	0	0	0	0	0	0

Spectrum order Industry Standard 24 pulse

Order	2	3	4	5	6	7	8	9	10	11	12	13	14	15	17	19	23
	25	29	31	35	37	41	43	47	49	53	55	59	61	65	67	71	73
Per unit value	0	0	0	0.92	0	0.43	0	0	0	0.09	0	0.09	0	0	0.09	0.09	0.65
	0.64	0.02	0.02	0	0	0	0	0.1	0.1	0	0	0	0	0	0	0.055	0.075

The harmonic spectrum data utilized has been taken from various operational installations and from factory specific tests. All of the data was compiled and averaged to give the most accurate spectrum and resulting prediction as possible.

RESULTS

Perfect Harmony Hybrid multi-pulse

Bus	Voltage Distortion					
ID	kV	Fund. %	RMS %	ASUM %	THD %	TIF
Bus1	25.000	100.00	100.00	100.52	0	0.53
Bus2	4.160	99.1	99.1	100.55	0.59	30.09

Bus	Current Distortion							
From Bus ID	kV	To Bus	Fund. Amp	RMS Amp	ASUM Amp	THD %	TIF	Balanced IT Amp -
Bus1	25.000	Bus2	37.8	37.8	38.94	1.41	28.2	1066.05
Bus2	4.160	Bus1	227.14	227.16	234.01	1.41	28.2	6406.53

Residual I*T does not apply to the Perfect Harmony design because of the delta secondary windings on the isolation transformer.

Industry Standard 24 pulse

Bus	Voltage Distortion					
ID	kV	Fund. %	RMS %	ASUM %	THD %	TIF
Bus1	25.000	100.00	100.00	100.02	0	0.68
Bus2	4.160	99.1	99.11	102.84	1.41	90.04

Bus	Current Distortion							
From Bus ID	kV	To Bus	Fund. Amp	RMS Amp	ASUM Amp	THD %	TIF	Balanced IT Amp -
Bus1	25.000	Bus2	37.8	37.8	39.14	1.46	65.19	2464.25
Bus2	4.160	Bus1	227.14	227.16	235.21	1.46	65.19	14809.19

Residual I*T does not apply to the standard design because of the delta secondary windings on the isolation transformer.

The data shown above indicates that all designs investigated meet IEEE 519:1992 for total harmonic distortion for this particular case. A specific harmonic prediction is required to ensure compliance in customer specific installations. The telephone interference standards for IEEE do not give specific levels to follow.

The results also show that the minimum configuration Perfect Harmony hybrid multi-pulse design (3 windings per phase) meets standards for telephone interference, highlighted at the balanced I*T product.

Other Considerations

There are several additional factors to consider when assessing input harmonic current performance. The gold standard in IEEE519 is to attain less than 5% ITHD at the transformer primary which is the most stringent requirement for the weakest distribution systems. But, the utility does not provide any extra credit for having less than 5%. Of course, from the utility perspective, there is “dilution” by the linear loads in a typical site, but, if you meet IEEE-519 at the drive input terminals, there is no question that it will be met at any point further up in the network assuming no other sources of harmonic currents are present on the power grid.

The balance of the customer's utility may dramatically affect the ITHD. If the unbalance is much more than 1%, then all diode rectifiers, regardless of the configuration, will begin to draw 3rd harmonic current and quickly fail to meet IEEE519.

The current waveform is determined largely by the transformer leakage impedance and because the transformer vendor must use an integer number of turns on the windings, the integer turns constraint will always result in non-ideal cancellation. So the detailed design of the transformer will have a significant effect on harmonic performance.

Conclusions:

Like many generalizations, one cannot arbitrarily say a 24-pulse rectifier is better for input harmonics than an 18-pulse rectifier. It is important to note that stating a VFD is 18 or 24 pulse does ***not*** mean it meets the relevant standards; it matters greatly what the actual topology is and must always be investigated to ensure compliance. The performance depends on many factors besides pulse number:

- The rectifier circuit topology; series or parallel, voltage-fed or current-fed.
- The total number of rectifiers. The series-cell multi-level topologies have three groups of multi-pulse rectifiers, and the normal variations in transformer parameters tend to reduce the higher order harmonics. So, frequently, an 18-pulse configuration of a series-cell multi-level VFD can be as good as or better than a 24-pulse configuration in another topology.
- The transformer impedance and the angle/amplitude accuracy. Higher impedance in the transformer slows the commutation which decreases the higher order harmonics.
- Utility source impedance.

Although multi-pulse techniques are very effective for reducing the harmonic signature of a VFD, they are not an unmixed blessing. Increasing the pulse number requires more components and must therefore lower the efficiency and reliability by some measure. There is no “extra credit” for better harmonic performance once you have met IEEE-519. Therefore, there is no reason to go to a higher pulse number if a lower pulse number will suffice. Using a higher pulse number means more components which has a reliability (and cost) penalty. By analysis, real world measurements and evaluation the Siemens18-pulse Perfect Harmony will meet the strictest limit of 519 for harmonic currents. It's generally agreed that having less than 5% current distortion is the equivalent of a linear load.

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