APPLICATION NOTE

Improving multi-pulse Drives with Active Filters

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Abstract

This application note describes the possibilities to improve multi-pulse drives by applying relatively small Active Filter to the installation. Multi-pulse drives have several problems that causes them to behave like a non-ideal multi-pulse drive, e.g., the 5th harmonic is not fully eliminated. By using a well-tuned Active Filter inside the Multi-pulse drive, the drive can be adjusted to have a perfect multi-pulse behavior. It furthermore gives the opportunity to compensate the residual harmonics of the drive with the available capacity of the Active Filter. These improvements can be achieved even by retrofitting an Active Filter into existing multi-pulse drive applications.

KEYWORDS: ACTIVE FILTERS, HARMONIC MITIGATION, MULTI-PULSE, 12-PULSE, 18-PULSE, RETROFIT

Background

The idea on multi-pulse drives is very simple and tempting. Using several 6-pulse drives on a special designed transformer with a phase-shift between them is supposed to reduce the amount of harmonic currents in the grid.

The intended benefits of multi-pulse drives are:

- Elimination of certain harmonics (see below)
- Tempting to use if you need a transformer anyway
- Transformer solution tend to be very reliable

There are some drawbacks of multi-pulse converter:

- Extra transformer is needed
- Not all harmonics will be removed
- Removed harmonics will not be fully removed
- Imperfections in the installation and transformer design will reduce the compensation capability
- Unbalance in the load or in the grid voltage reduced the compensation capability

It is possible to calculate the number of harmonics a drive will create as follow:

$$h = n * p \pm 1$$

With n a counter and p the number of pulses, it is possible to calculate the expected harmonics h.

Using a 6-pulse converter, the formula will find several harmonics that will be created by the drive, 5/7; 11/13; 17/19; 23/25; 29/31; 35/37; 41/43; 47/49

Using a 12-pulse converter the formula will show much fewer harmonics, 11/13; 23/25; 35/37; 47/49

Using a 18-pulse converter the formula will show even fewer harmonics, 17/19; 35/37

Using a 24-pulse converter the formula will show also very few harmonics, 23/25; 47/49

To do this, a 12-pulse converter is using a phase-shift transformer, typically something like a Dy11Dd0. Such a transformer does have two output strands with a phase-shift between them. In this case the phase shift on the first leg would be 0° and on the second leg would be -30°. An 18-pulse converter will do the same with typically a 0°, -20° and +20° phase shift. 24-pulse converter are using typically 0°, -15°, 15° and 30° phase shift.

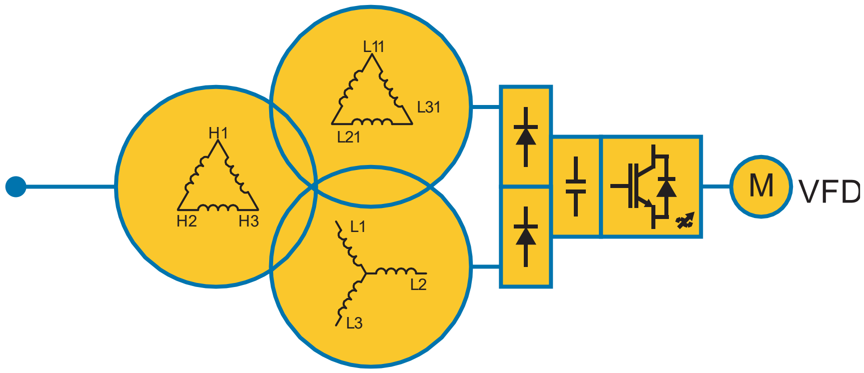


Figure 1: 12-pulse converter with Dy11Dd0 transformer

This shift in the phase has the effect that the harmonics of side one and the harmonics of side two are not in the same direction. There are two ways how to visualize that. First as a waveform where the start of the sine-wave is now 30° shifted on one side towards the other side. A 30° shift on the fundamental will result in a much larger shift in a harmonic. The shift will be X-times the 30° where X is the harmonic order, since the 5th harmonic order has 5 times the fundamental frequency. For example, this means a phase-shift on the fundamental of 30° will cause a phase shift of the 5th harmonic of 5*30°=150° towards the 5th harmonic of the other leg.

A phase-shift of +/-180° would cancel out the 5th harmonic completely. A phase shift of 150° will result in some 5th harmonic residual current on the grid.

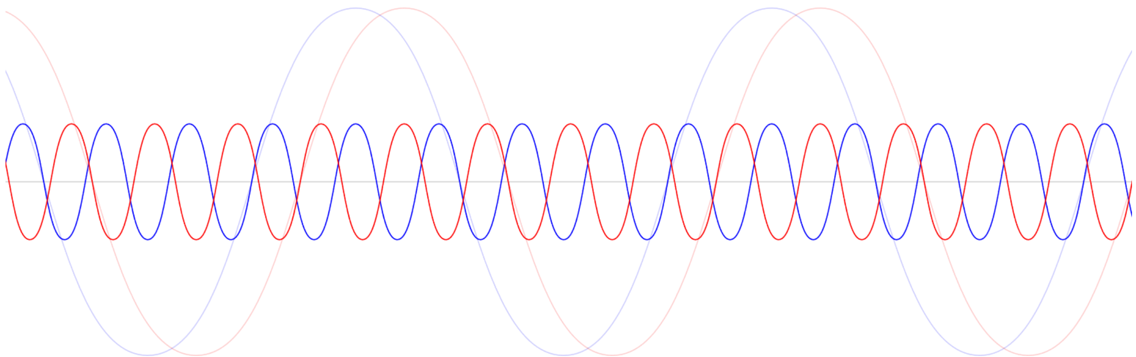


Figure 2: Phase-shift visualized in the waveform of fundamental and 5th harmonic

The other way to visualize this is based on a vector diagram. The 5th harmonic has an amplitude as well as a direction. The direction of the 5th of both legs can be summed up to find the amplitude and direction of the resulting harmonic on the grid.

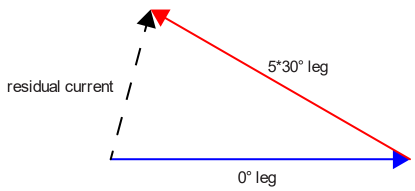
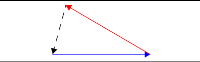
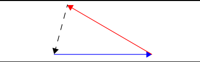
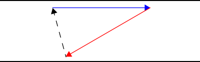
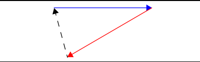
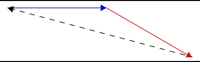
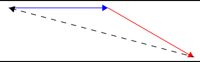
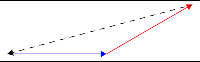
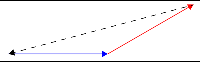
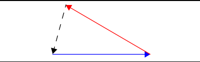
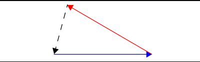
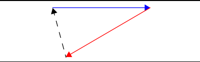
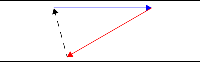
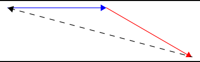
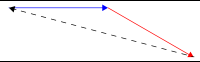
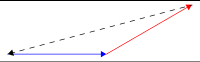
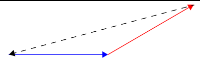


Figure 3: Vector diagram of 5th harmonics in a 12-pulse converter

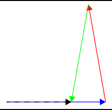
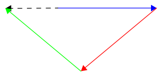
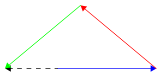
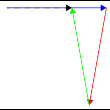
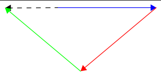
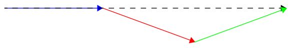
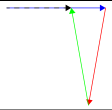
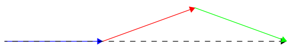
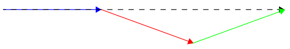
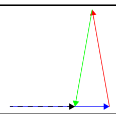
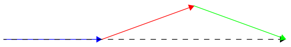
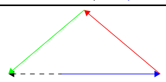
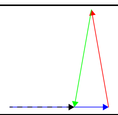
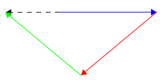
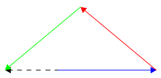
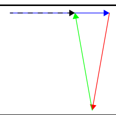
In both cases it can be seen that the harmonics will be reduced. However, it also gets clear quickly that the harmonic will not disappear completely. This is the case for all multi-pulse drives and all harmonics in these drives.

To remove the 5th harmonic completely from the grid, a phase-shift of -36° would be needed to reach exactly -180° and a full compensation. This is much more difficult to realize in a transformer. Looking further, the 7th harmonic would need a phase-shift of -25° and the -36° needed for the 5th harmonic are in fact not more negative for the 7th harmonic. Therefore the 30° is uses as a compromise.

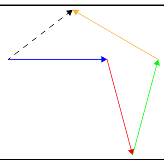
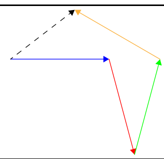
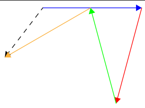
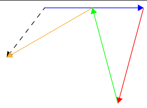
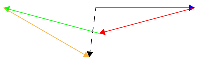
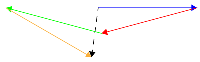
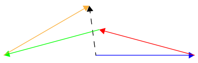
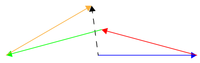
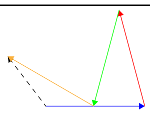
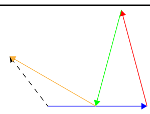
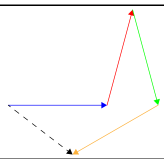
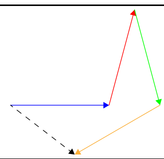
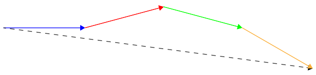
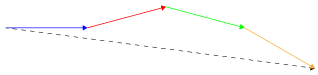
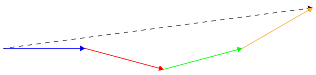
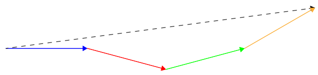
Summation of harmonics in a 12-pulse converter

Harmonic	Phase angle of harmonics	Graphical summation of legs	Harmonic	Phase angle of harmonics	Graphical summation of legs
5th	0°/150°		29th	0°/150°	
7th	0°/-150°		31st	0°/-150°	
11th	0°/-30°		35th	0°/-30°	
13th	0°/30°		37th	0°/30°	
17th	0°/150°		41st	0°/150°	
19th	0°/-150°		43rd	0°/-150°	
23rd	0°/-30°		47th	0°/-30°	
25th	0°/30°		49th	0°/30°	

Summation of harmonics in an 18-pulse converter

Harmonic	Phase angle of harmonics	Graphical summation of legs	Harmonic	Phase angle of harmonics	Graphical summation of legs
5th	0°/100°/-100°		29th	0°/-140°/140°	
7th	0°/140°/-140°		31st	0°/-100°/100°	
11th	0°/-140°/140°		35th	0°/-20°/20	
13th	0°/-100°/100°		37th	0°/20°/-20°	
17th	0°/-20°/20		41st	0°/100°/-100°	
19th	0°/20°/-20°		43rd	0°/140°/-140°	
23rd	0°/100°/-100°		47th	0°/-140°/140°	
25th	0°/140°/-140°		49th	0°/-100°/100°	

Summation of harmonics in a 24-pulse converter

Harmonic	Phase angle of harmonics	Graphical summation of legs	Harmonic	Phase angle of harmonics	Graphical summation of legs
5th	0°/-105°/105°/30°		29th	0°/-105°/105°/30°	
7th	0°/-75°/75°/-30°		31st	0°/-75°/75°/-30°	
11th	0°/-15°/15°/-150°		35th	0°/-15°/15°/-150°	
13th	0°/15°/-15°/150°		37th	0°/15°/-15°/150°	
17th	0°/75°/-75°/30°		41st	0°/75°/-75°/30°	
19th	0°/105°/-105°/-30°		43rd	0°/105°/-105°/-30°	
23rd	0°/165°/-165°/-150°		47th	0°/165°/-165°/-150°	
25th	0°/-165°/165°/150		49th	0°/-165°/165°/150	

Adding an imbalance to the load or the grid voltage will make this behavior even worse.

This Application Note will from now-on use the vector diagram to visualize the harmonics compensation.

Improvement 1: Active Filter on the primary side

Quite straight forward is the approach in adding an Active Filter to the primary side of a multi-pulse drive. At this stage, the drive was already doing its job in reducing the harmonics like the 5th and 7th in a 12-pulse converter and the Active Filter can be added to take care of the rest. This cannot be done if the primary side of the transformer is above 690 V when using ADF; in this case, see option 2 below.

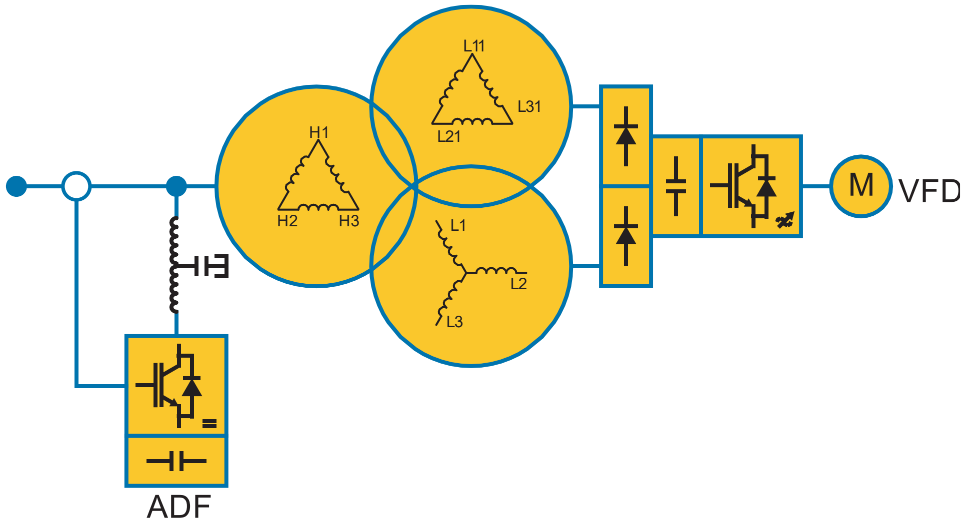


Figure 4: 12-pulse converter with Active Filter on primary side

Improvement 2: Active Filter measurement on the secondary side

To be able to compensate also if the primary side is MV, it is possible to only install the current sensors of the Active Filter on the MV side of the grid. In this case the Filter will see what is missing in the compensation and it can provide this current on the LV side of the transformer. This approach is only working if the Active Filter is connected to the side of the phase-shifting transformer that has a 0° phase shift.

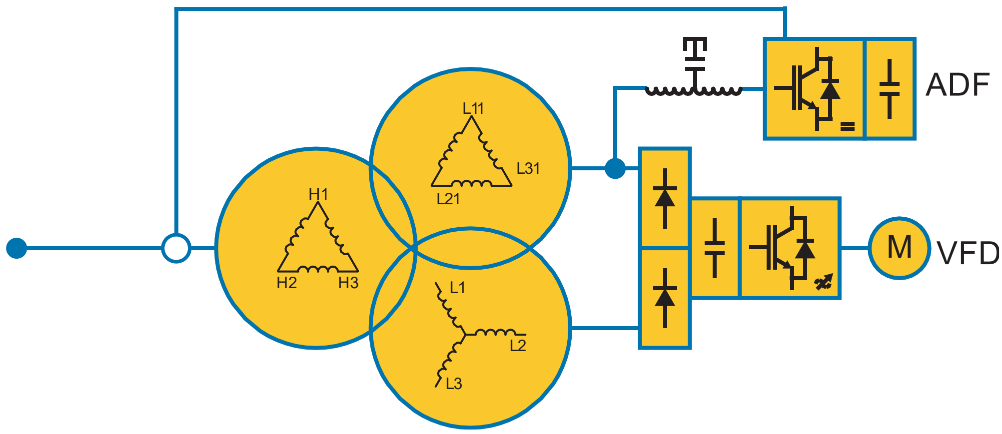


Figure 5: 12-pulse converter with Active Filter measurement on the MV side

This approach however only works with 12-pulse converter. In 18-pulse or 24-pulse, the leg with the Active Filter connected would have a much bigger amount of harmonics during the compensation and this would potentially overload the transformer.

Improvement 3: Active Filter on each secondary side

It is possible to build an ideal multi-pulse drive by adding one small Active Filter on every leg of the phase-shifting transformer. A quality Active Filter like the Comsys ADF series can be configured to achieve an ideal multi-pulse solution especially when running in open-loop, due to the ability to define the amount of harmonic compensation current that needs to be created and the angle in which this harmonic current is pointing.

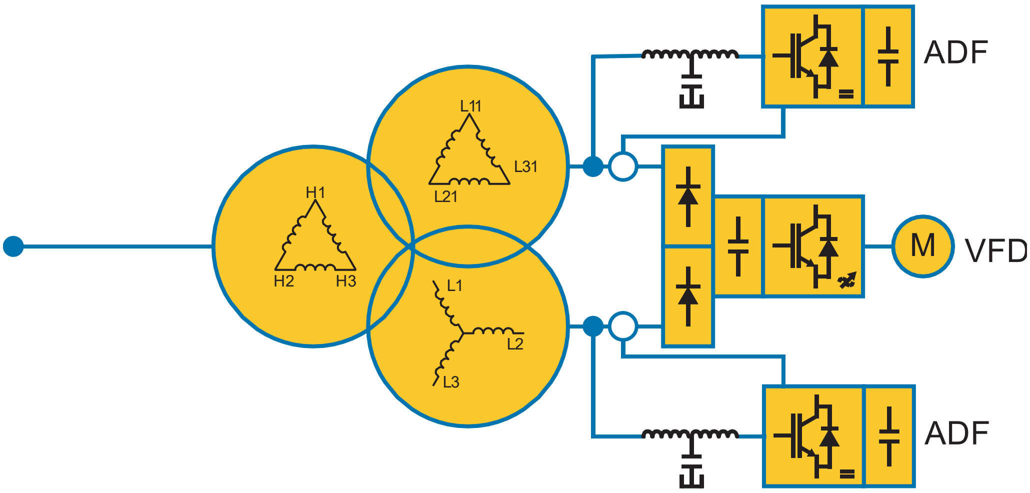


Figure 6: 12-pulse converter with Active Filter on each leg

Using this approach, it is possible to adjust for the imperfect transformer design.

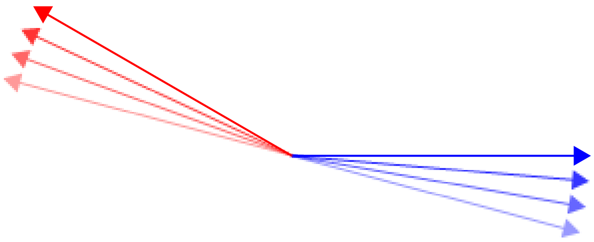


Figure 7: Shifting the different legs in a multi-pluse converter

In this diagram it can be seen that the angles of the 5th harmonic are not perfectly opposite to each other. Moving the blue in one direction or the red current in the other direction could improve this. It is also possible to move both and therefore not as much. This can be done by the Active Filter.

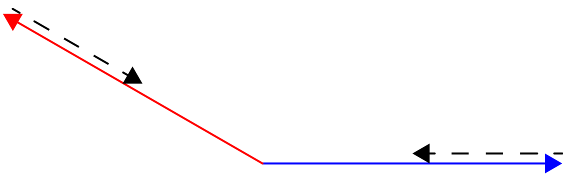


Figure 8: Traditional compensation with an active filter

Normally the Active Filter is only adding a compensation current and by this approach is reducing the amount of harmonic current in the network. With the fine-tuning as it is possible with the Comsys ADF, it is possible to also adjust the angle of the compensation current. By this the resulting 5th harmonic current will change the direction.

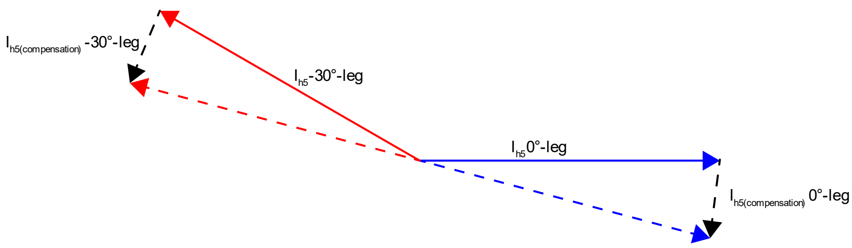


Figure 9: Compensation with an Active Filter and adjusted direction of compensation

In this example with a 12-pulse converter, the two legs are 30° off from a perfect 180° signal. With the 180°, the two harmonics would cancel out in the 12-pulse transformer. To get the two harmonic currents in that direction, it is possible to adjust the active filter compensation current and move the harmonics with this.

The best result is achieved when the amplitude of the harmonic after compensation is the same as before compensation. The compensation could be done only on one leg, but to get the most flexible result it is better to do this compensation on each of the multi-pulse legs.

Finding the right adjustment angle as well as the compensation amplitude is a simple trigonometric calculation.

We will take the 5th harmonic as an example and do the calculations for a 12-pulse/18-pulse and 24-pulse converter.

As seen in the table above, the 5th harmonic on a 12-pulse converter has 0° and 150° phase-shift. The difference to 180° is 30°. This can now be compensated on each side, so 15° each. The amplitude results out of the sine-law with:

$$\frac{a}{sin(A)} = \frac{b}{sin(B)} = \frac{c}{sin(C)}$$

Where A is the angle opposite the side a and B is the angle opposite side b and C is the angle opposite side c.

$$\begin{aligned} a &= I_{h5(compensation)}0°leg \\ A &= 15° \\ b &= I_{h5}0°leg \\ B &= \frac{180° - 15°}{2} \\ I_{h5(compensation)}0°leg &= \frac{I_{h5}0°leg * \sin 15°}{\sin\frac{180° - 15°}{2}} \\ I_{h5(compensation)}0°leg &= I_{h5}0°leg * 0.261 \end{aligned}$$

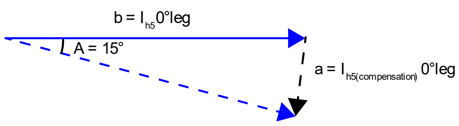


Figure 10: Graphical representation of the calculation above

This shows that to compensate the 5th harmonic in a 12-pulse drive, 26.1% of the harmonic current is needed.

12-pulse converter adjustment table:

Harmonic	Leg 1	Leg 2	Compensation	Filter 1 adjustments	Filter 2 adjustments
5th	-15°	+15°	26.1%	-82.5°	+82.5°
7th	+15°	-15°	26.1%	+82.5°	-82.5°
11th	+75°	-75°	121.8%*	0°*	0°*
13th	-75°	+75°	121.8%*	0°*	0°*
17th	-15°	+15°	26.1%	-82.5°	+82.5°
19th	+15°	-15°	26.1%	+82.5°	-82.5°
23rd	+75°	-75°	121.8%*	0°*	0°*
25th	-75°	+75°	121.8%*	0°*	0°*
29th	-15°	+15°	26.1%	-82.5°	+82.5°
31st	+15°	-15°	26.1%	+82.5°	-82.5°
35th	+75°	-75°	121.8%*	0°*	0°*
37th	-75°	+75°	121.8%*	0°*	0°*
41st	-15°	+15°	26.1%	-82.5°	+82.5°
43rd	+15°	-15°	26.1%	+82.5°	-82.5°
47th	+75°	-75°	121.8%*	0°*	0°*
49th	-75°	+75°	121.8%*	0°*	0°*

18-pulse converter adjustment table:

Harmonic	Leg 1	Leg 2	Leg 3	Compen-sation	Filter 1 adjustments	Filter 2 adjustments	Filter 3 adjustments
5th	-	+20°	-20°	34.7%	0°*	+80°	-80°
7th	-	-20°	+20°	34.7%	0°*	-80°	+80°
11th	-	+20°	-20°	34.7%	0°*	+80°	-80°
13th	-	-20°	+20°	34.7%	0°*	-80°	+80°
17th	-	-100°	+100°	153.2%*	0°*	0°*	0°*
19th	-	+100°	-100°	153.2%*	0°*	0°*	0°*
23rd	-	+20°	-20°	34.7%	0°*	+80°	-80°
25th	-	-20°	+20°	34.7%	0°*	-80°	+80°
29th	-	+20°	-20°	34.7%	0°*	+80°	-80°
31st	-	-20°	+20°	34.7%	0°*	-80°	+80°
35th	-	-100°	+100°	153.2%*	0°*	0°*	0°*
37th	-	+100°	-100°	153.2%*	0°*	0°*	0°*
41st	-	+20°	-20°	34.7%	0°*	+80°	-80°
43rd	-	-20°	+20°	34.7%	0°*	-80°	+80°
47th	-	+20°	-20°	34.7%	0°*	+80°	-80°
49th	-	-20°	+20°	34.7%	0°*	-80°	+80°

24-pulse converter adjustment table:

Harmonic	Leg 1	Leg 2	Leg 3	Leg 4	Compen-sation	Filter 1 adjust-ments	Filter 2 adjust-ments	Filter 3 adjust-ments	Filter 4 adjust-ments
5th	-15°	-15°	+15°	+15°	26.1%	-82.5°	-82.5°	+82.5°	+82.5°
7th	+15°	+15°	-15°	-15°	26.1%	+82.5°	+82.5°	-82.5°	-82.5°
11th	+7.5°	-7.5°	-7.5°	+7.5°	13.1%	+86.25°	-86.25°	-86.25°	+86.25°
13th	-7.5°	+7.5°	+7.5°	-7.5°	13.1%	-86.25°	+86.25°	+86.25°	-86.25°
17th	-15°	-15°	+15°	+15°	26.1%	-82.5°	-82.5°	+82.5°	+82.5°
19th	+15°	+15°	-15°	-15°	26.1%	+82.5°	+82.5°	-82.5°	-82.5°
23rd	+75°	+75°	-75°	-75°	121.8%*	0°*	0°*	0°*	0°*
25th	-75°	-75°	+75°	+75°	121.8%*	0°*	0°*	0°*	0°*
29th	-15°	-15°	+15°	+15°	26.1%	-82.5°	-82.5°	+82.5°	+82.5°
31st	+15°	+15°	-15°	-15°	26.1%	+82.5°	+82.5°	-82.5°	-82.5°
35th	+7.5°	-7.5°	-7.5°	+7.5°	13.1%	+86.25°	-86.25°	-86.25°	+86.25°
37th	-7.5°	+7.5°	+7.5°	-7.5°	13.1%	-86.25°	+86.25°	+86.25°	-86.25°
41st	-15°	-15°	+15°	+15°	26.1%	-82.5°	-82.5°	+82.5°	+82.5°
43rd	+15°	+15°	-15°	-15°	26.1%	+82.5°	+82.5°	-82.5°	-82.5°
47th	+75°	+75°	-75°	-75°	121.8%*	0°*	0°*	0°*	0°*
49th	-75°	-75°	+75°	+75°	121.8%*	0°*	0°*	0°*	0°*

* Here it is more efficient to just compensate the harmonics without using the phase-shift

Improvement 4: Two Active Filter on each secondary side plus some intelligence

The improvement 3 already shows how to compensate for the non-ideal phase shift in the multi-pulse transformer. Beside that, the drive, the grid and the actual physical design of the transformer can bring in more imperfections due to unbalances to the multi-pulse setup. It can happen that the 5^{th} harmonic on one side is 200 A while on the other side we only have 150 A. Even adjusting for the transformer is not enough to compensate for this imperfection.

Here it is possible with the Comsys ADFs to reach a near perfect result, by adding a PLC into the loop. The ADF Active Filter do have Modbus TCP where it is possible to read out the amplitude of each and every single harmonic. With the possibility to adjust the settings of the ADF on the fly, it is possible to calculate the perfect way of compensation for both sides and send this information back to the ADFs.

The calculations seen in the previous section need to be implemented into the PLC. The needed data can be pulled directly from the ADFs on the secondary side. The needed adjustments of phase angle and amplitude can be done on the fly via Modbus TCP.

This way some of the most important drawbacks of a multi-pulse converter can be reduced.

Discussion and Summary

We have shown in this application note that:

- Even an ideal multi-pulse transformer is “non-ideal” in the way it compensate the harmonics.
- Applying an ADF into a multi-pulse application can improve the compensation in various ways.

In many cases retrofit is possible as transformer will not be overloaded by adding ADF since harmonic current flow is just “moved” in the transformer, however total harmonic footprint will be reduced on feeding grid.

With an ADF on the primary side, the filter works in a conventional way and can reduce total harmonic footprint. In 12-pulse solutions, a single ADF on the secondary side can improve the deficiencies of the multi-pulse solution, including both the inherent properties (e.g., “12-pulse harmonic” of order 11, 13 and so on) but also the intrinsic asymmetries as well as the residual by-products such as the 5^{th} harmonic order.

The proposed solutions are attractive when multi-pulse was previously enough, but the demands have increased, but also to mitigate problematic harmonics in large installations. In particular, these solutions are attractive in retrofit cases, but can also be deployed in new installations where the customer have stringent demands but need a transformer anyway.