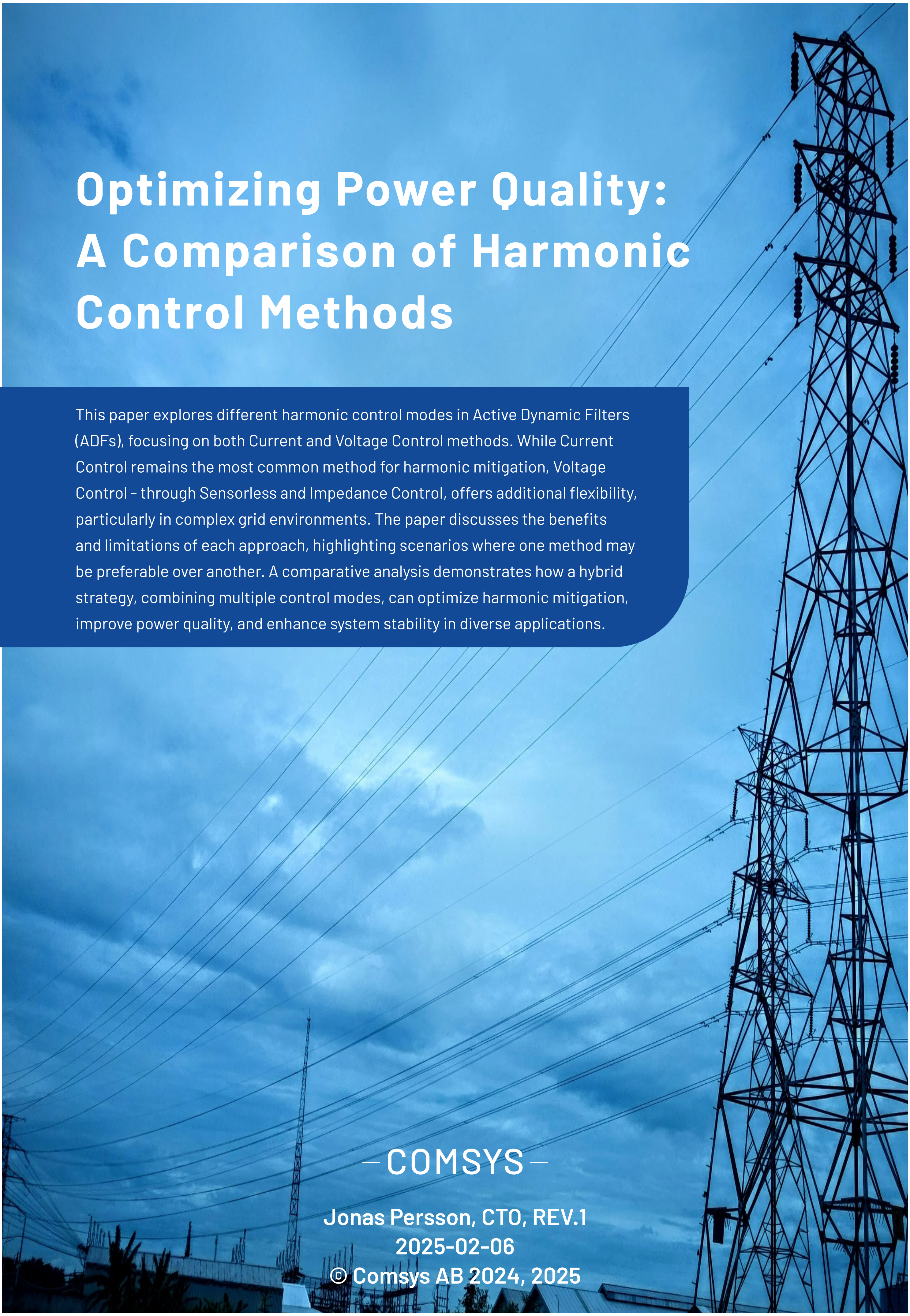

Optimizing Power Quality: A Comparison of Harmonic Control Methods

This paper explores different harmonic control modes in Active Dynamic Filters (ADFs), focusing on both Current and Voltage Control methods. While Current Control remains the most common method for harmonic mitigation, Voltage Control - through Sensorless and Impedance Control, offers additional flexibility, particularly in complex grid environments. The paper discusses the benefits and limitations of each approach, highlighting scenarios where one method may be preferable over another. A comparative analysis demonstrates how a hybrid strategy, combining multiple control modes, can optimize harmonic mitigation, improve power quality, and enhance system stability in diverse applications.

COMSYS

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BACKGROUND

Historically, active harmonic filters (including Comsys ADF offerings) relied on Current control only. The principle is simple; the active filter observes a current on the grid (typically via a Current Transformer (CT)), calculates a necessary compensation current to the grid, and injects said current. Current control can then further be divided into closed loop- and open loop control; the former means the active filter sees the result of the injected current, while the latter means the active filter cannot see the result.

Later, the ADF (Active Dynamic Filter) line of active filters from Comsys introduced two novel approaches for compensation of harmonics on the grid: Sensorless control and Impedance control. These two control types, and their respective benefits and drawbacks will shortly be discussed in this text. Throughout the remainder of this text, an active filter is simply referred to as an ADF.

This text focuses predominantly on the control modes available in the ADF P25, ADF P100 and ADF P300 series of active power quality filters; the context of this discussion is Harmonics only.

EFFECTS OF HARMONIC ISSUES

As early as 2010, the first iterations of the control types utilizing Voltage control were introduced. Voltage control is what it sounds like – the ADF compensates harmonics by observing only the mains voltage. In other words, no CT is needed when using Voltage control (however, see the section on mixing harmonics below). Initially, the idea of Voltage control was to simply be able to compensate for voltage harmonics without observing the grid current. This is convenient in locations where it is complex to measure the source current or load current, notably in marine applications with several generators and in applications with several split bus bars or ring grids. This type of control is simply called Sensorless control, which is the first of two Voltage control modes.

Second, the idea was to apply an impedance to the grid. This can be done in several ways (wideband, narrowband, etc.), however the idea was simply to control the harmonics by lowering the impedance of the grid. This type of control is called Impedance control.

A summary of the four basic control types is presented in Table 1, located on the following page.

Current Control		Voltage Control	
Closed Loop	Open Loop	Sensorless control	Impedance control
The ADF sees the result of the compensation, e.g., the CT is placed upstream to the ADF	The ADF does not observe the result of the compensation, e.g., the CT is placed downstream of the ADF (on the load).	The ADF observes voltage harmonics on the grid and calculates the necessary compensation current via a mathematical model. This method is closed loop by nature.	The ADF behaves like an (active) impedance on the grid. Therefore, voltage harmonics lead to an injection of current. This method is not closed loop nor open loop.

The following sections will go into more detail on each of the two Voltage control modes.

SENSORLESS CONTROL

With Sensorless control, the ability to compensate voltage harmonics without a CT (Current Transformer) was introduced. The main benefit of the function is that no CT is needed; however, additional benefits were quickly discovered in a number of applications. In some applications, the benefit of not having to install CTs is huge; it may be practically hard or non-feasible to install CTs in cases with multiple feeders, such as marine applications, split bus-bar applications, ring networks or networks with emergency power. In these cases, it is strongly recommended to deploy either Sensorless control (or Impedance control, as to be discussed in the next section).

Sensorless control works by observing the grid voltage, and specifically the voltage harmonics. For each harmonic, a correction current is calculated. A major difference in comparison with current control is the way settings are applied to the system; in current control, a setting of 50% means that the ADF tries to remove 50% of the observed harmonic current at the specific order. This is not possible in Sensorless control, due to the simple fact that we are observing the grid voltage and compensating the grid voltage. As soon as compensation is started, it is impossible for the ADF to know the grid voltage of the harmonic prior to compensation since we do not know the full state of the grid or the load. This means a setting of 50% is equivalent to limiting the maximum allowed current output of the ADF to 50% of its rated current at the specified order. As a side effect, it is more difficult to fine tune Sensorless control to a certain degree of compensation than Current control.

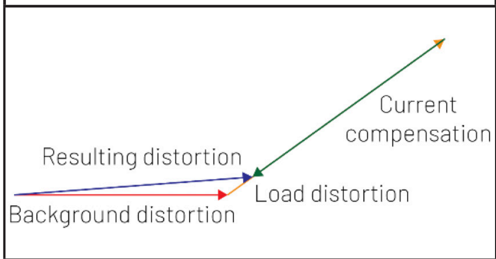
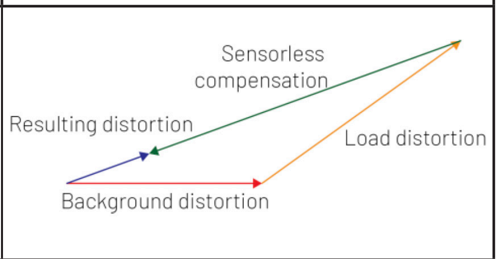
Since the ADF does not know the impedance of the grid, a mathematical model is used to convert the measured voltage distortion into a compensation current. However, this leads to a major difference between current control and Sensorless control – in the former, we observe the grid current (closed loop) or the load current (open loop) and then use this to calculate the compensation current.

In the latter case, we monitor the grid voltage, which reflects a combination of two key distortion sources: load-related distortion (caused by the connected equipment or nonlinear loads) and background distortion (inherent within the grid itself due to upstream factors such as upstream harmonic resonance, neighboring loads, or grid imperfections).

Being able to address both background distortion and load-related distortion is a significant advantage. This capability allows for a more holistic approach to reducing overall voltage distortion. Unlike conventional current control systems, which primarily target the harmonics generated by the load, Sensorless control observes and responds to the grid voltage directly. By compensating for both local and external sources of distortion, Sensorless control can achieve superior performance.

In practice, this means that with an equivalent compensation capacity, Sensorless control often yields lower voltage total harmonic distortion (THDU) compared to current control. This is because it dynamically adjusts to grid conditions, mitigating not only load-induced harmonics but also the broader harmonic spectrum present in the grid. As a result, Sensorless control provides more robust and efficient harmonic suppression, leading to improved power quality.

This is illustrated in the figures below. In Current control, the ADF can only act on the load distortion (as observed from the current). In Sensorless control, the ADF can act on the resultant of the load distortion and background distortion, utilizing the available compensation current in the most efficient manner possible. In scenarios like this, the difference between Current control and Sensorless control depends on the amount of background distortion and the phase shift between the background distortion and load distortion.

Current Control	Sensorless control
	

Like Current control with closed loop operation, Multi-master mode is required for parallel operation to prevent individual ADF units from counteracting each other.

IMPEDANCE CONTROL

In other control types, the impedance of the grid is changed as a side-effect of the compensation. Adding an ADF with Current control and activating the 5^{th} harmonic effectively results in a lowered impedance at the 5^{th} harmonic only. However, this is a side effect. What happens when we try to directly influence the impedance of the grid? This is the purpose of Impedance control.

In conventional control types, a harmonic is observed, and mitigated by means of a controller tracking the harmonic at hand (for sake of completeness, it shall be mentioned that there are wideband control types, not targeting a single harmonic). In Impedance control, the purpose of the control is to insert an (active) impedance into the grid. This is done by observing the grid voltage and calculating the corresponding current of the virtual impedance. The calculated current is the injected into the grid – the ADF works as an active impedance. In other words, Impedance control is a form of Voltage control.

This is usable for mitigating harmonic voltages, simply by lowering the impedance at the frequencies where the voltage is high resulting in lower voltage distortion – with a given load current, a lower impedance at a harmonic frequency corresponds to a lower harmonic voltage. Like in Sensorless control, it does not matter if the source of the distortion is from the grid or load side.

In the case of a resonance, the difference becomes substantial. The problem with a resonance is a significantly increased impedance in the grid, causing very high voltage harmonics when the resonance is excited. The most indirect way of mitigating the resonance is by compensating the current that excites the resonance (using Current control). However, this does not change the resonance per se; it only avoids exciting the resonance. In the case of Sensorless control, we attack the problem more directly by lowering the voltage harmonics. Still, the resonance is not directly handled – we solve the problem by handling the symptoms (the load current triggering the resonance, or the voltage harmonics caused by the resonance), however the source of the resonance – the impedance of the grid – is left untouched. As a side effect, the grid behaves as if the impedance was changed.

Using Impedance control, we have the opportunity to actually change the grid behavior by lowering the impedance at the resonant frequency, without any change in the reactive impedances (capacitance and inductance) causing the resonance. In Impedance control, the immediate purpose of the compensation is to change the impedance, and as a side effect, we get the desired result that the voltage harmonics are reduced, and the grid becomes more benign.

When using an ADF P25/P100/P300 in Impedance control mode, the user setting when parametrizing the filter is somewhat counterintuitive. Setting a value of 100% at for example 5th harmonic means that the ADF is inserting the lowest possible impedance at that frequency. Backing off on the setting means increasing the inserted impedance or lowering the interaction with the grid. This is intuitive in the way that a higher number in the setting results in stronger interaction/mitigation. In the ADF P25/P100/P300, Impedance control works by inserting a narrow-band impedance at each harmonic frequency (e.g., 5th order, 7th order, and so forth). This differs from the ADF P200 which inserts a wide-band impedance, covering several frequencies and harmonic orders at once. However, the abstract way of doing the parametrization makes Impedance control more user-friendly in ADF P25/P100/P300 units.

Inserting a constant impedance (same for all frequencies) to the grid, as can be done with the ADF P200, is a good idea for mitigating resonance, especially in cases where the resonance is moving in frequency over time. The reason is that the interaction with the grid will be the strongest where the grid impedance is the highest, i.e., at the point of the resonance. The next best option is to have possibility of inserting a low impedance at discrete harmonics, which is the case with ADF P25/P100/P300.

In general, having access to Impedance control in any installed ADF is invaluable – usually resonances are not planned, and have the potential to cause huge problems if they occur. Being able to mitigate them with an already installed equipment is a major advantage. The wideband impedance control, making a flat impedance possible, can also mitigate interharmonics.

Due to the nature of impedance control, it is significantly more stable than Sensorless control and especially Current control, allowing operation in very weak grids with very strong resonances. A positive side effect of this behavior is that it is possible to combine several ADF units using Impedance control on the same grid without adverse effects. A benefit of this is that ADFs can be grouped on bus bars in split bus bar configurations, and the operation will remain stable during all modes of operation, without requiring any Multi-master configuration.

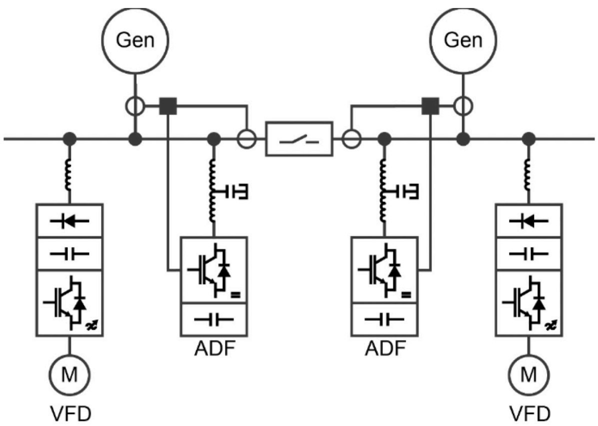
It shall be noted that a particular variant of impedance control has been available in the ADF P200 for a long time.

CURRENT CONTROL

But what about Current control? Are there no use cases for Current control? Yes, there are. First, Current control is the standard way of mitigating harmonics using ADF units in the industry – it is a tried and tested solution with a good track record. Second, there are some use cases where Current control is the preferred solution:

- When expanding a facility, and the desire is to maintain status quo, Current control in open-loop configuration can be used to minimize the impact of new loads. In other words, the placement of the CTs will determine what load the ADF "sees" and limit the mitigation to only that load.
- When expanding a facility as in the above paragraph, Current control can also be used in closed-loop configuration to reduce the impact of the new load, however in this case the new load cannot be pinpointed.
- When bundling the ADF with load, essentially creating a Low harmonic version of existing equipment, a specified distortion level of the load can be guaranteed. In a bundled solution, both closed loop and open loop control is feasible.
- To meet a certain current distortion level, typically TDD levels specified in IEEE 519. Since the ADF is directly interacting with the current harmonics in Current control, guarantees can be made of the desired target level. This is not possible in Voltage control. In practice, current distortion is also improved when using Sensorless or Impedance control, but to various degrees.

A recurring drawback of Current control is the need to size the CT ratio in an appropriate way. In Open loop sizing is trivial – the CT must be able to see the full load current. In Closed loop the sizing might be less apparent – the CT must be large enough to see the entire current in the facility. In cases with multiple ADF units and multiple power sources, CT setup becomes complex, with requirements on wiring, cable length and summation CT in addition to the meter CTs. A typical example of this complexity is illustrated in the diagram below.



As can be seen, the setup is complex with multiple measurement points being tied to a summation transformer, and then the secondary of the summation transformer must be routed through all the ADF units. In the case of a bus tie or emergency generator setup, complexity increases further. A practical problem can be that the measurement resolution becomes poor due to the total equivalent CT ratio.

Further, in Open loop applications, the CTs may require calibration if low residual harmonic levels are required. Doing the calibration in the user interface is simple, however external measurement devices must be used. In some cases, it is hard or impractical to perform this calibration, as it must be performed on site.

COMPARING CONTROL TYPES

In the following section, we will discuss the pros and cons of the different control types. In general, the obvious difference between Current Control and Voltage Control is that the former requires CTs, and the latter does not. Another obvious difference is that Voltage Control can affect background distortion, while current control cannot. However, the opposite is also true; only Current Control can isolate the load distortion – which may be desirable when attempting to compensate only a specific load.

	Current Control		**Voltage Control**	
	Closed loop	**Open loop**	**Sensorless**	**Impedance**
Requires CT?	Y	Y	N	N
Multi-master required for parallel?	Y	N	Y	N
Settings distributed over Multi-master?	Y	Y	Y	Y
Combat background distortion (Keep distortion out)	N	N	Y	Y
Combat only load distortion	Y	Y	N	N
Can resultant grid current distortion be observed?	Y	N	Y[1]	Y[1]
Can load current be estimated?	Y	Y	N	N
Resonance mitigation	Indirectly by avoiding excitation		Indirectly via voltage	Directly
Meet a specified level of current harmonics / demand distortion	Y	Y	N	N
Stability in resonant grids	Good	Good	Good	Best

[1] If CT is installed

ADF P100/P300 are able to use Multi-master control. Multi-master is a way to synchronize two or more ADF units to distribute loading between the systems and allow a single system to be taken down for maintenance while the other systems continue to operate and share the load, all of that dynamically.

In Current Control and Sensorless Control, the ADF units dynamically share the load via bus communication while using Multi-master. In Impedance Control, Multi-master is not needed for parallel operation, as there is no load to share – the systems instead insert an impedance to the grid. Due to the control design, ADF units running Impedance Control remain stable even during very low load levels (distortion levels) and do not start to compete or counter each other. Still, Multi-master can be used to distribute settings between the systems. Technically speaking, Multi-master is not needed for Open loop Control, but recommended for synchronization purposes.

A common problem when sizing for Current control is the uncertainty of the (voltage) background distortion. High levels of background distortion may negatively impact the ability to reach the required voltage distortion. In those cases, Sensorless Control gives a definitive advantage over Current Control.

Voltage Control schemes can also be used in cases where most of the distortion to be mitigated is background distortion. An example of this is when a sensitive load (for example a Remote Operated Vehicle, ROV) is fed from a lower voltage (e.g., 480V) and the primary (e.g., 600V) has heavy distortion from for example DC drives. In those cases, Voltage Control can be used to “keep distortion out” from the lower voltage grid. This works especially well if the impedance of the feeding transformer is high, reducing the size of the needed ADF.

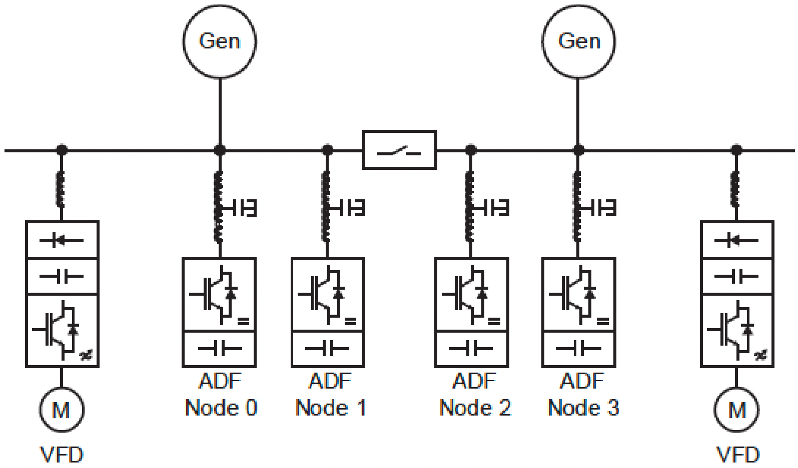
Due to the nature of Sensorless Control, it is more efficient to lower voltage harmonics for a given size of the active filter than Impedance Control. This is related to the feedback in the control loop. In other words, if it is not necessary to lower the grid impedance, but just the voltage distortion, Sensorless Control may be a better option than Impedance Control.

However, it may not be necessary to use only a single control mode – the pros and cons can be combined in the same system by mixing control types, described in the next section.

MULTI-MASTER AND NODE MASKING

In addition to multi-master control, the Node masking functionality can be used to determine when a system is included in Multi-master control. The most common example is when a group of systems are split over a bus divided into two parts (split system with a bus tie, for example in marine applications).

Consider the following example:



In this system, we have two main buses divided by a bus tie, and two ADF units per side. Units are numbered 0...3. When setting up the system, we can use the systems as one large group, allowing all systems to compensate the total load. When the bus tie is open, a secondary compensation set is used. In this case, Node masking is used to limit the number of system in each group, so that system 0 and 1 only "see" system 0 and 1. This means that system 0 and 1 are now in its own group, and only see the loads on the left bus. The same is applied for units 2 and 3.

Bus tie position	**Compensation set**	**Node mask**	
		0, 1	2, 3
Closed	Primary	0, 1, 2, 3	0, 1, 2, 3
Open	Secondary	0, 1	2, 3

This concept allows very flexible configuration to various network setups and applications.

MIXING CONTROL TYPES

Using ADF P25/P100/P300, it is possible to mix compensation types for different harmonics. This means that the user can mix and match operation modes for different harmonic order, for example using Current Control for order 5th, 7th, 11th and 13th, while simultaneously in the same system enabling Impedance control for harmonic orders 17th, 19th, 23rd and 25th. The user might desire to control the current distortion, first enabling Current Control for all harmonic order to be compensated between 5th and 49th. The user then discovers while commissioning the system that a resonance is active between 17th and 19th harmonic. In this case, the ADF can operate in Impedance Control on orders 17th and 19th, while simultaneously compensating all the other harmonic orders in Current Control.

Another possibility is to switch compensation type as a function of Compensation set. In this case, an external PLC or similar equipment will send command to the ADF via field bus (typically Modbus/TCP or Ethernet/IP) or via relay control, switching the compensation set. A typical example is to run the ADF in Current Control when it is connected to the grid, meeting IEEE 519 requirements, but switching to Impedance Control in emergency mode when operating on Diesel Generators, guaranteeing a stable operation while off-grid.

The ability to mix control types in the ADF P25/P100/P300 series of products is unprecedented, and allows for great flexibility in designing a system to mitigate all kinds of harmonic-related problems and situations.

SIZING

In this section, differences in the methodology for sizing ADF units for different control types will be briefly discussed. This is, however, not intended as a comprehensive guide to sizing.

For Current control, the simple method of sizing an ADF is to measure, simulate or calculate the needed current to compensate the load. For certain loads, for example diode rectifiers with low impedance, the commutation may be affected by the ADF. In those cases, the calculated current must be increased. In normal cases, the increase in harmonic current to the diode rectifier can be around 10-30%; in extreme cases, for example with no DC or AC choke at all in weak grids, the increase in current to the rectifier may exceed 50%. All these effects are taken into account in the ADF Sizing Tool.

For Sensorless control, the sizing requires slightly more data. Input data is the source impedance of the grid, the voltage harmonics in the worst-case scenario, and the target level of the compensation. From this data, the source grid is treated as a Thevenin equivalent, and the needed compensation current is calculated as the current needed to cause the voltage drop from the worst-case level to the target level. The calculation is simple if the user has access to the appropriate tools. In most cases, calculating the needed compensation level for both Current control and Sensorless ontrol yields a smaller ADF for Sensorless control, especially if the target level is on the voltage.

For Impedance control, the mitigation factor is equivalent to the ratio between the grid impedance and the minimum output impedance of the ADF configuration. Since it is difficult or impractical to obtain the actual grid impedance prior to installation it is hard to perform impedance control sizings in practice. However, in most cases when Impedance control is necessary, a resonance is in place, making the grid impedance higher than expected, the mitigation ratio will in practice be high enough. Again, due to the differences in feedback between Sensorless control and Impedance control, the former usually results in lower residual harmonics, if both control types can be run. Having said that, if a resonance is known prior to installation, the safest choice may be the ADF P200.

SUMMARY

In this short paper, voltage control modes have been discussed and compared to current control modes. In general, voltage control modes are favorable when background distortion is a concern, or when the lowest possible voltage harmonic residual is desired, or when attempting to "keep distortion out" from a feeding dirty grid. A major benefit of voltage control is the ability to compensate voltage distortion without CTs, greatly simplifying installation requirements especially in complex setups.

Impedance control is a specialized control mode that allows for zero configuration parallel operation without needing Multi-master configuration, which is beneficial in applications with multiple power sources, multiple/split bus bars systems and similar configurations. Impedance control is suitable for lowering or controlling the source impedance and for combating resonance problems.

A specific benefit of Impedance control is the ability to work robustly in parallel even during changing grid conditions, without any risk of instability, further simplifying installation even compared to Sensorless control which requires Multi-master in those setups.

On the other hand, Sensorless control is more efficient than Impedance control if the target is the lowest possible residual voltage harmonics.

Current control still has a place, especially when the target is to limit the impact of a single machine or equipment, or when the goal is to modify said equipment into a low harmonic device (e.g., modifying a 6-pulse variable speed drive to a low harmonic drive). Current control may also be necessary when the user must guarantee a certain level of current distortion (typically demand distortion according to IEEE 519).

A major benefit of the ADF P25/P100/P300 is the ability to mix control types in the same system, allowing the user unprecedented flexibility in tailoring the system to the needs of the site. A typical example is combating resonance using impedance control at certain harmonics, or controlling lower harmonic orders with current control and higher harmonic order with one of the voltage control modes.

In addition to this, Multi master with Node masking allows a great deal of flexibility when installing in network setups with bus ties and similar applications.

In summary, the various control modes available in the ADF P25/P100/P300 contribute to making it the most comprehensive power quality toolbox in the market.