Technical Note 060

Active front end drive versus active filter solutions

Decentralized vs. centralized mitigation strategies

There is a wide selection of harmonic mitigating solutions available for variable frequency drives. Having a variety of solutions offers flexibility to an engineer. However, navigating through marketing data and an assortment of terminology from various vendors can be challenging. After a brief review on harmonics and drive technology, Technical Note 060 describes, compares, and contrasts two of those mitigation solutions – an active front end drive compared to an active filter installed in front of multiple 6-pulse drives. ABB offers both solutions. Typically, the active front end drive is the optimal mitigation solution for most installations, but there are some installations where an active filter may be a preferred solution.

Harmonics

Standard drives, along with many other electronic devices, draw current in a non-linear fashion. The non-linear consumption of current from the power grid creates current distortion, which in turn creates voltage distortion. The amount of distortion is expressed in a percentage of the fundamental frequency. THD_I is the total harmonic current distortion. THD_V is the total harmonic voltage distortion. TDD is the total demand distortion, which is essentially the current distortion of the system during maximum demand period of the facility. The higher the percentage of the THD_V or TDD value, the worse the harmonics are in that facility. Documents such as Harmonics in HVAC are available to learn more about harmonics.

Standard 6-pulse drives

The industry standard drive is also known as a 6-pulse drive. The term *6-pulse* comes from the fact the drive has a quantity of six diodes in the rectifier circuit. A drive fundamentally works by rectifying AC to DC, storing the energy on DC bus capacitors, then the inverter section creates a variable AC voltage to the motor. The gray box in Figure 1 shows the combination of the diode-based rectifier and the DC bus capacitors. This combination is what creates power line harmonics.

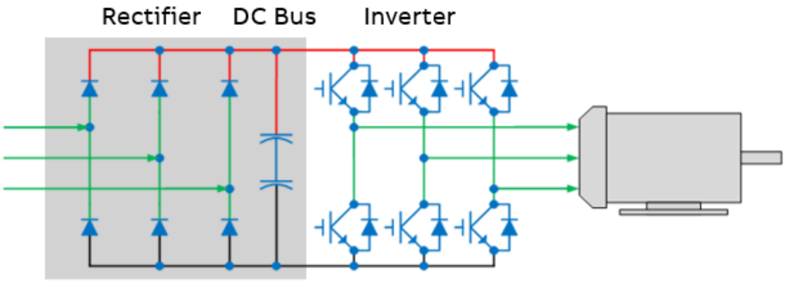


Figure 1 6-pulse drive schematic

THD_I measured at the drive's input lugs, while under full load, is the traditional way to compare harmonic levels between different mitigation solutions. A 6-pulse drive with no internal impedance has a THD_I of around 80%, but can reach as high as 120 % with some designs. An input AC line reactor or DC bus chokes can be added to a 6-pulse drive, to bring the THD_I down into a 35 - 50% range.

Active front end drives

An active front end (AFE) drive uses insulated gate bipolar transistors (IGBTs) instead of diodes in the rectifier circuit. As shown in Figure 2, there is also an LCL (inductor-capacitor-inductor) filter included with an AFE drive. The combination of the front end's actively controlled IGBTs, along with the LCL filter, allows the AFE drive to draw current almost linearly, and not creating the troublesome harmonics in the first place. The DC bus and inverter section of an AFE drive are essentially the same as on a 6-pulse drive. AFE drives have a very low THD_I of 3 - 5%, with ABB's latest generation Ultra-low harmonic (ULH) AFE drive offering THD_I performance below 3%.

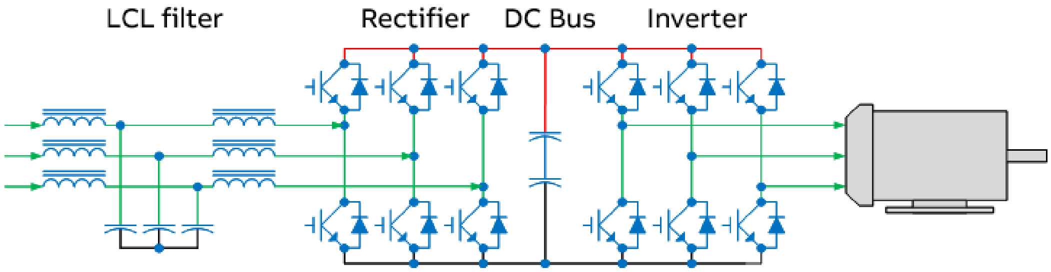


Figure 2 Active front end drive schematic

Active filters

Active filters work like noise canceling headphones. The active filter monitors the harmonics on the power line, and injects harmonics of equal magnitude but opposite polarity, to essentially cancel out the harmonics. Active filter components are similar to AFE drives, in that they include inductors, capacitors, and transistors. An active filter also requires interfacing to externally installed current sensors. Active filters usually come in large metal enclosures, and are connected in parallel to the building electrical bus. While adding a single active filter for each drive is technically feasible, this solution is incredibly expensive on systems with multiple drives. An active filter is typically installed on an electrical bus upstream of the panel feeding the drives, such that the filter cleans up harmonics from all the drives at once. Active filters are sized based on how many Amps of harmonics need to be canceled out.

Decentralized versus centralized mitigation solutions

On a new project, an engineer must first make a high-level decision on the facility's harmonic mitigation; either go with a decentralized approach or a centralized approach. A decentralized approach places the mitigation at the drive. A centralized approach has a single location that cleans up harmonics. While decentralized solutions include AFE drives, they also include other harmonic mitigation methods such as drives with external passive filters or 18-pulse drives. Centralized solutions use a single active filter location to clean up harmonics. There are also some hybrid solutions where active filters are placed through the facility at different levels of switchgear and panels, but due to cost these solutions are rare and limited to very large facilities.

Table 1 on the following page compares a decentralized with a centralized mitigation strategy. While many of the decentralized topics are applicable to non-AFE solutions too, such as passive filters, Table 1 assumes an AFE solution for the decentralized approach.

Table 1: Decentralized versus centralized comparison

Topic	Decentralized (AFE)	Centralized (active filter)
Protects the grid (outside the building)	✓	✓
Protects the building, harmonics not created	✓	
Allows for smaller wire size within the building	✓	
Allows for smaller fuses, breakers, switchgear	✓	
Highest cost (in most scenarios)		✗
Bring existing facility into IEEE 519 compliance	✓	✓
~No THD_I related losses over the cables (I^2R)	✓	
Emergency backup generator friendly	✓	✓
Single point-of-failure (and fault conditions)		✗
Wiring independence for service	✓	
Easy 1:1 sizing of mitigation equipment	✓	
Power factor improvement (utility bill)	✓	✓
Consider power factor improvement in sizing		✗
Additional specialist to support start-up / service		✗
Common mode voltage impact	✗	
Free input power sub-metering	✓	
Cost impact on fully redundant drive systems	✗	
Cost impact (oversize) for tie breaker systems		✗
Unexpected system interactions		✗

The following sections go into greater detail on the topics found in Table 1:

Protects the grid (outside the building)

- An AFE drive does not create meaningful levels of harmonics therefor does not impact the utility grid outside of the facility.
- An active filter cancels current harmonics at the filter. Everything upstream of the active filter will be protected from harmonics.

Protects the building, harmonics not created

- An AFE drive does not create meaningful levels of harmonics in the first place, thus the building is not exposed to harmonics from drives.
- An active filter has no impact on the current distortion downstream of the filter. The current distortion still exists in the building, which leads to a degree of voltage distortion. The amount of voltage distortion is dependent on system impedances.

Allows for smaller wire size within the building

- AFE drives draw less current than 6-pulse drives. This allows for smaller wire to be used, as the wire is sized based on the input current rating of the drive. As an example, below are (3) different 480 VAC ABB drives that are all rated 30 HP.
  - 6-pulse drive with no impedance (ACS320): 56 Amp input current rating
  - 6-pulse drive with DC bus choke (ACH580-01): 44 Amp input current rating
  - AFE drive (ACH580-31): 34 Amp input current rating
- An active filter has minimal impact on input current draw of a drive.

Allows for smaller fuses, breakers, switchgear

- Similar to the wire size comments above, the drive's lower current consumption has a cumulative approach throughout the network allowing for smaller fuses and/or breakers and can ultimately lead to smaller switchgear being used. This can result in both cost and space savings.
- An active filter leads to larger gear, as there must be room for the active filter itself

Highest cost

- Using AFE drives as required to comply with IEEE 519 is typically the lowest cost solution.
- The active filter solution can occasionally be lowest cost for IEEE 519 compliance when there is a high volume of only small VFDs, i.e. quantity 150, 3 HP drives. Typical installations, with a mix of smaller and larger drives, result in an active filter as a more expensive solution.

Bring existing facility into IEEE 519 compliance

- An AFE drive solution is applicable when the existing drives are near end-of-life and due for replacement. However, if most of the existing drives are new, then the AFE drive solution is not ideal for existing systems that are failing IEEE 519. This is because the existing 6-pulse drives would need to be removed and replaced with an AFE drive. Future drives could be AFE drives.
- An active filter is an ideal solution when a system is failing IEEE 519, has a high volume of drives early in their lifecycle, and the building must be brought back into compliance to avoid utility penalties.

~No THD_I related losses over the cables (I^2R)

- AFE drives don't create any meaningful level of harmonics in the first place. As a result, there are no harmonic related losses over the wire.
- An active filter does not clean up current distortion downstream of the filter. There are harmonic current related losses that cause the power cables wires to run hotter.

Emergency backup generator friendly

- The minimal AFE drive harmonics do not interfere with the voltage regulation of a generator. A generator will operate fine with AFE drive loading.
- Active filters clean up harmonics upstream of the filter, so systems are designed with the generator upstream of the filter. Active filters are compatible with generators assuming the active filter is online and functioning. Note that the generators that relay on active filter, must have the generator oversized to be able to handle the situation where an active filter were to fail or go offline.

Single point-of-failure (and fault conditions)

- Decentralized solutions, like AFE drives, have the mitigation integral with the drive. If there was a failure or a fault, only that one drive is "down" and unavailable.
- Active filter centralized solutions inherently have single point-of-failure concerns. Engineers designing systems containing emergency generators should consider filter failure scenarios as part of the design of the filtering scheme and generator sizing. Generators trip offline when exposed to high levels of harmonics, thus an active filter failure can cause a generator to shut down. Active filters can also shut down due to a fault that requires manual reset.
    - Parallel active filters can be used to provide some degree of back-up. These solutions are more expensive and found in larger systems that require significant harmonic mitigation. Even with parallel filters, there is often single point-of-failure components, such as shared current sensors.

Wiring independence for service

- Most drives are independent from each other. If work is needed on a single drive, then only that drive is taken offline.
- Taking a single active filter offline to work on the filter results in the facility losing all harmonic mitigation. Parallel active filters often share components and wiring. This means to safely work on one active filter module, the entire active filtering solution may need to be taken offline for a period of time.

Easy 1:1 sizing of mitigation equipment

- AFE drives have the mitigation built into the design of the drive. There are no external devices to size or coordinate with.
- Active filters are challenging to size optimally. Sizing requires knowledge on how many Amps of harmonics need to be removed. Additional sizing consideration (oversizing) is required if the filter will be used to improve system power factor. Modules jump in sizes, such as 50 A, 100 A, and 300 A. A system requiring 220 A of mitigation will likely result in a 300 A filter solution, resulting in the owner paying for 80 A of capacity they won't use. Active filter manufacturers recommend all downstream VFDs have a reactor or choke. Moving this added cost downstream to the drive allows the active filter to be sized smaller. Note that due to the voltage drop across the reactor, certain drives such as low uF

DC bus designs and ECMs, are not compatible with AC line reactors being added.

Power factor improvement (utility bill) & Consider power factor improvement in sizing

- AFE drives naturally have a 1.0 unity true/total power factor. They can also be programmed to inject additional positive or negative kVAR into the network to offset existing power factor issues.
- Active filters can also provide power factor improvement, but they must be sized to do so. Failure to account for power factor correction during the design stage may result in an active filter sized only to handle harmonic mitigation.

Additional specialist to support start-up / service

- The drive manufacturer handles start-up of the AFE drive. Unless there are specific requests, such as adding extra kVAR, the start-up of an AFE drive is identical to that of a 6-pulse drive. No specialized owner training is required for the AFE drive, as the interface is the same as a 6-pulse drive.
- The active filter specialists are typically going to be different from the drive specialists. In many cases the active filter and drives are supplied by two different manufacturers. Owner training specific to the active filter is required.

Common mode voltage impact

- AFE drives are known to create more common mode voltage (CMV) than 6-pulse drives. Higher levels of CMV is known to increase the likelihood of motor bearing currents. ABB addresses this fact with additional CMV filtering within the drive design. For example, the ABB's ACH580 ULH drives come from the factory with CMV filters included. When specifying AFE drives, engineers should include CMV filters as an AFE drive specification item, and/or specify motors with integral grounding brushes.
- Active filters do not impact CMV.

Free input power sub-metering

- AFE drives monitor input power to the drive. This information is helpful to learn more about where the power is being consumed within their facility. Data for that piece of equipment can be trended over time.
- Active filters also have valuable data available, however the data is only for that one physical location within the electrical network. Data is not available for the individual pieces of equipment downstream of the active filter.

Cost impact on fully redundant drive systems

- Some system or equipment designs have a primary drive and a backup drive. The backup drive only runs when the primary drive is unavailable. In that case, having AFE technology on the backup drive adds cost that is unnecessary far more than 99.9% of the operating time.
    - Alternative decentralized mitigation solutions can be explored, such as using a lower cost 6-pulse with DC bus choke approach for the backup drive.
- Active filters become more economical with system designs with a high number of redundant / backup drives. The active filter is sized based only on the drives that are operating under load.

Cost impact (oversize) for tie breaker systems

- AFE drives do not require any special consideration or cost increase for tie breaker systems. These are systems where drives could be fed from multiple different utility transformers. AFE drives are ideal for these installations.
- Active filters are sized based on the Amps of harmonic mitigation needed. Closing of a tie breaker will add additional harmonic loading to that utility transformer and active filter. The active filter must be sized to handle this worst-case scenario. Engineers should consult with their active filter vendors before implementing a tie breaker control scheme and active filter sizing, as various active filter vendors approach these situations differently. Reference the section *Systems with tie breakers* later in this document for more information on tie breaker configurations.

Unexpected system interactions

- AFE drives are designed to prevent the drive from creating harmonics and include an LCL filter. This combination prevents those unexpected electrical system interactions.
- Active filters inject harmonics at a high switching frequency. Those new harmonics are intended to cancel out existing harmonics. There are cases where the high frequency switching addition of new harmonics will interact with other devices on the network. For example, EMC filters on downstream 6-pulse drives may try to filter that high frequency switching noise, resulting in EMC filter failure. Some active filter designs allow adjustments to detune the performance of the filter to prevent unexpected system interactions. As a result of detuning, the filter will clean up less harmonic content.

One-line diagrams for decentralized and centralized solutions

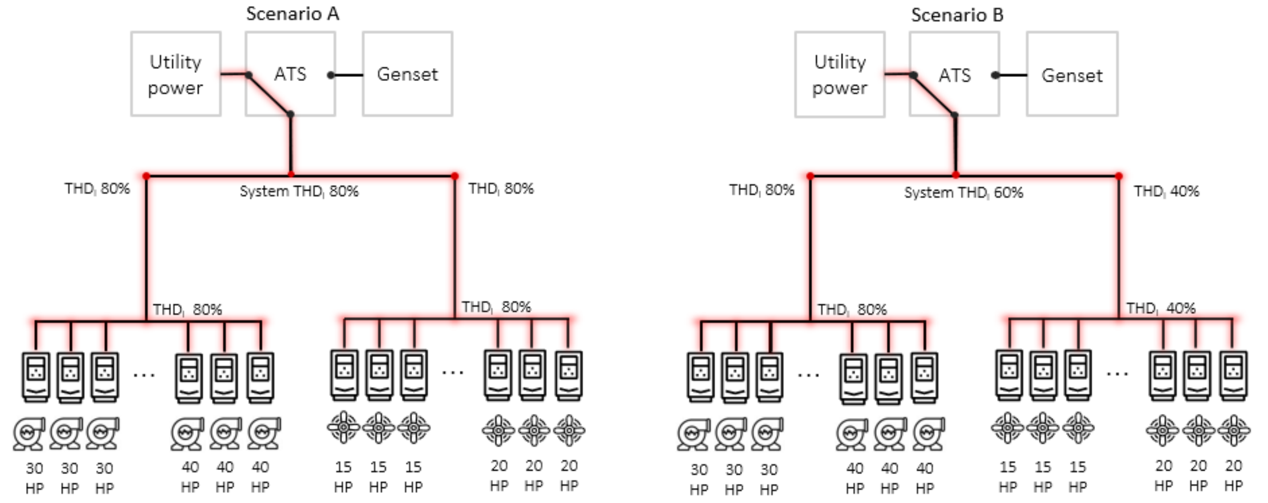
The following figures and examples illustrate and reinforce many of the topics just covered. We will start with decentralized examples beginning with drives with no mitigation and work our way through various hardware configurations, up until all the drives are AFE, all while looking at the overall system impact of each example. An equivalent centralized strategy is then reviewed with a centralized active filter strategy. Tie breaker configurations, along with systems with generator backup, are also reviewed with both decentralized and centralized mitigation strategies. For simplicity, all the examples will only include drive loads, with no other linear or non-linear loads. THD$_I$ is used to compare the scenarios. One-line diagram wires highlighted in red require a degree of oversizing due to harmonic currents.

Decentralized one-line diagram examples

Figure 3 shows two different system designs side by side. Scenario A shows 300 HP of pump drives with no mitigation on the left branch and 300 HP of fan drives with no mitigation on the right branch. This results in an extremely high 80% THD$_I$ on both the left and right branches, and thus 80% THD$_I$ throughout the system. This magnitude of harmonic currents results in a 1.28x factor in oversizing of the wires. Scenario A is shown as a starting point to build the remaining examples from and would not be recommended for a proper system design.

How is the above 1.28x oversize factor calculated? As an example, let's look at the left branch with the fan drives in Scenario A. Assume they are on a 480 VAC network and draw a combined 400 Amps of fundamental current. As stated in Scenario A, there is 80% harmonic current, which would be 320 Amps of harmonic current. The resulting math results in an equation of $(\sqrt{400^2+320^2}) / 400 = 1.28$x oversize factor due to harmonics.

Scenario B in Figure 3 upgrades the fan drives to include 5% impedance chokes. Scenario B results in 40% THD$_I$ on the right branch and the system average is brought down to 60% THD$_I$. The 40% THD$_I$ results in a 1.08x oversize factor on the right branch wires, while the 60% THD$_I$ portion results in a 1.17x oversize factor at the switchgear level. While Scenario B has improved the overall THD$_I$ to 60%, this is still not a proper system design even after linear loading factored in.



300 HP pump VFDs, no mitigation | 300 HP fan VFDs, no mitigation

300 HP pump VFDs, no mitigation | 300 HP total fan VFDs, w/chokes

Figure 3 No mitigation and limited mitigation

Figure 4 explores what happens when AFE drives are introduced into the system in a decentralized mitigation approach. In Scenario C, the pump drives are upgraded to an AFE design. Note how the THD_I of the left branch has been drastically reduced to 3% and the system THD_I is reduced from 60% to 21.5%. With 3% current distortion in the left branch, the oversize factor is only 1.001x, and can be ignored.

In Scenario D, all the drives are AFE technology, so there is no oversizing required as the overall system harmonics are only 3% THD_I which meets and exceeds the requirements of IEEE 519-2014. Scenario D is the easiest way to make sure the system meetings IEEE 519-2014, but may not be the most cost optimized solution. A solution somewhere between Scenario C and Scenario D, with a mix of AFE drives on the largest units, and 6-pulse drives with chokes on the smallest units, is typically the lowest cost solution that complies with IEEE 519-2014.

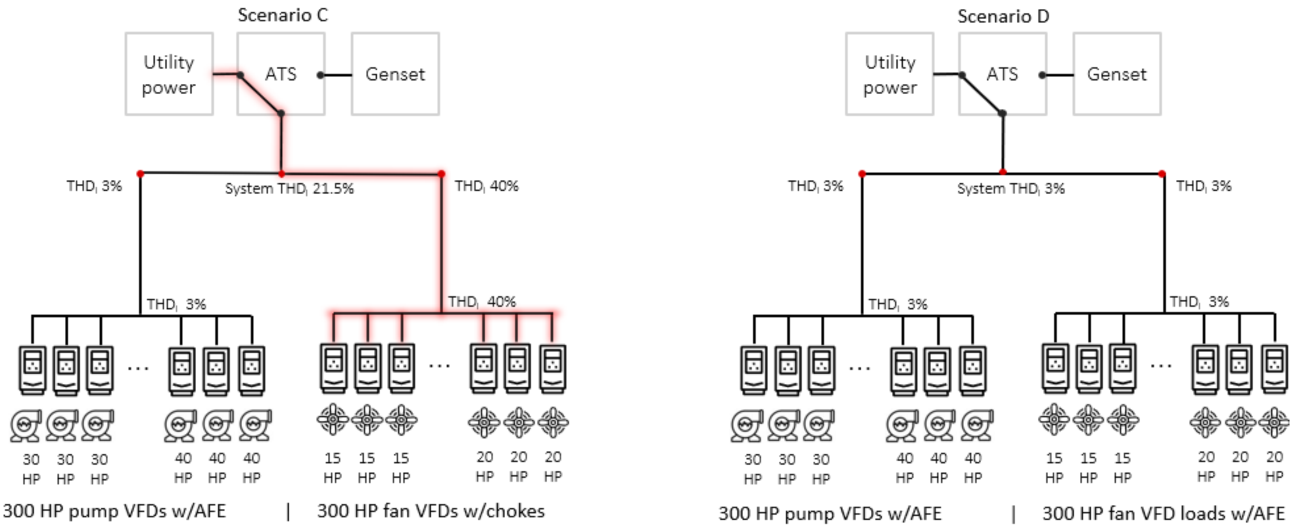


Figure 4 Active front end drive impact

Centralized one-line diagram examples

Figure 5 transitions to a centralized mitigation solution of an active filter that cleans up harmonics from downstream 6-pulse drives. The 6-pulse drives have integral chokes. Scenario E shows a system functioning as expected, with the active filter cleaning up the harmonics from the downstream drives. The downstream wires still are exposed to the 40% THD_I, so there is the oversizing factor of 1.08x.

Scenario F shows a situation where the active filter is offline. An active filter could go offline for numerous reasons, such as a nuisance fault that requires a manual reset, to a component failure that requires service of the active filter. The utility is now exposed to all the harmonics being generated by this facility. This puts the facility at risk of being penalized (charged) by the utility. During this period, the voltage distortion will increase significantly within the facility, as now the upstream utility transformer is exposed to the current distortion. Exposing a transformer to current distortion leads to voltage distortion from that transformer. This voltage distortion is distributed to the entire electrical network. Voltage distortion can lead to a variety of problems within an electrical network.

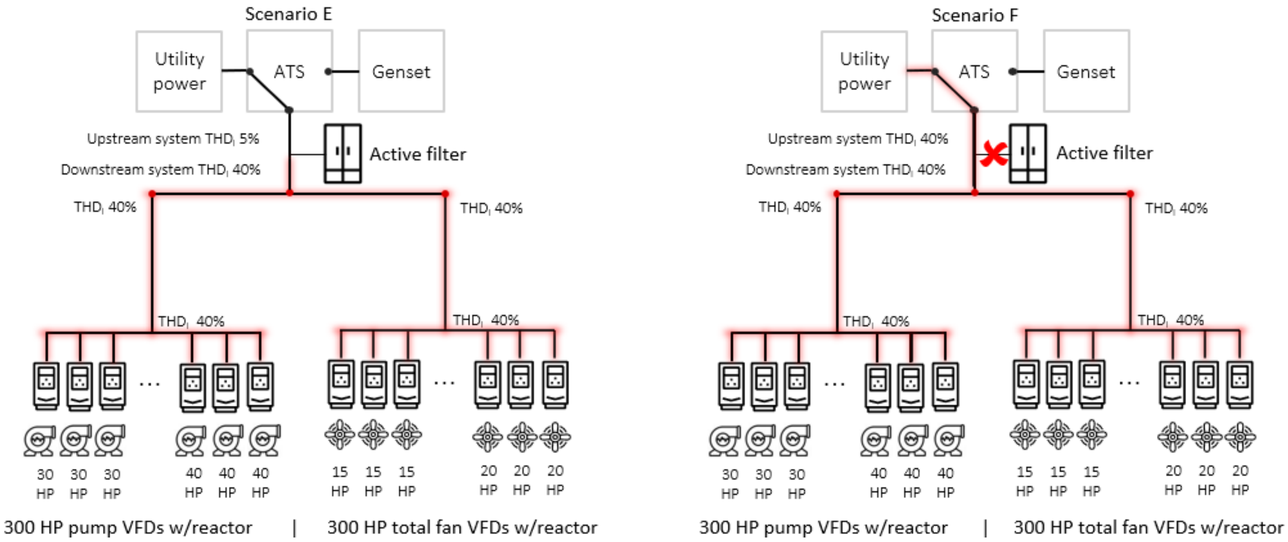


Figure 5 With and without an active filter online

Systems with tie breakers

Larger facilities, especially critical facilities, often have systems designed with tie breakers. This electrical scheme typically has more than one utility power source feeding the facility. Figure 6 shows a tie breaker network with a decentralized harmonic mitigation approach using AFE drives. During normal operation the tie breaker is open, and each half of the network is independent. However, if utility power is lost to one half of the system, such as a transformer failure, both halves of the network can be fed from a single power source. Using Figure 6 as an example for the sequence of operations, utility power source #2 is lost, the tie breaker closes, and now the entire network is supplied by utility power source #1. In these situations, the utility power source transformers are typically oversized, and this operating condition is meant to be temporary until the other source is returned.

Decentralized mitigation solutions, such as ones using AFE drives, are ideal for tie breaker networks. AFE drives do not create any meaningful harmonics magnitudes in the first place. As a result, additional AFE drives can now be fed from utility source #1, as shown in Figure 6, without burdening utility source #1 with significant harmonic loading.

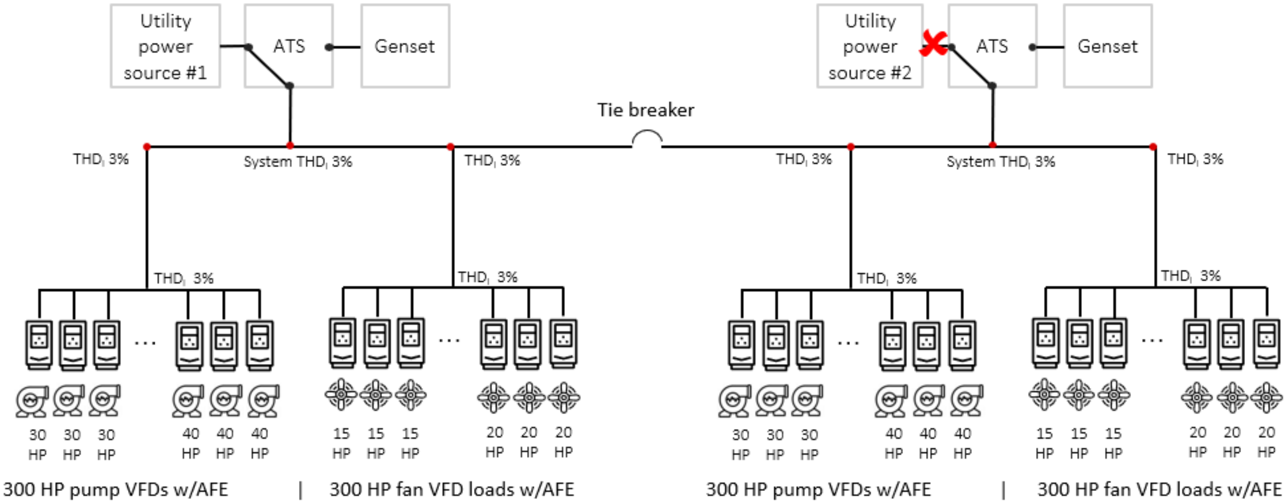


Figure 6 Tie breaker with decentralized mitigation approach

How does the centralized mitigation approach compare to the decentralized mitigation solution previously shown in Figure 6? Figure 7 shows the same utility power source failure scenario, except now we are using a centralized harmonic mitigation approach using active filters. The system in Figure 7 shows independent active filters for each side of the system, active filter #1 and #2. Active filters #1 and #2 only filter harmonics for their respective utility power sources or gensets, and cannot assist one another if no power is flowing past them. With the tie breaker closed, active filter #1 is responsible for mitigating the entire network. This means the size of both active filters should be doubled (oversized). If the active filter is not oversized, then utility power source #1 will be exposed to higher levels of harmonics at a time when that power source is already pushed to its design limits. Engineers must consider this situation during the system design and simulation stage, and if they choose not to oversize the active filters, then the transformers must be further oversized to handle the extra harmonic loading. Whether putting the oversizing cost in the active filter or the upsized transformer, either solution is more expensive than a decentralized approach with AFE drives.

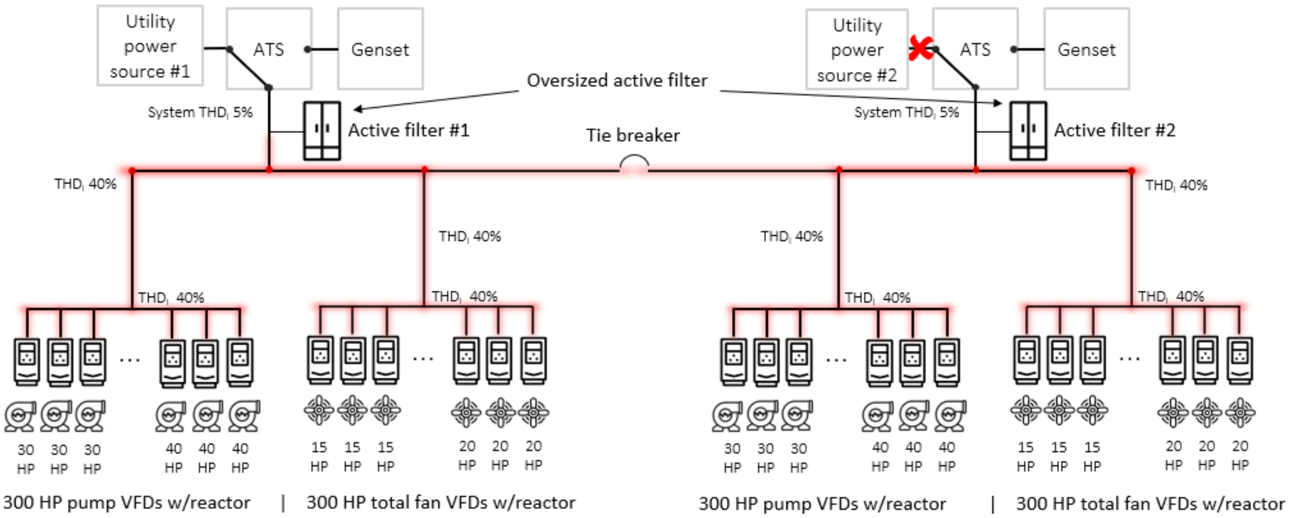


Figure 7 Tie breaker with centralized mitigation approach

Impact on generators

The previous examples focused on electrical networks fed from utility power. What about when the network is fed from a backup generator? Critical facilities, such as hospitals and data centers, have backup generators. IEEE 519-2014 Table 2 subnote "c" recommends TDD (current distortion) be kept to 5% or less on generator power sources.

Decentralized Scenarios A and B (Figure 3) should not be used for systems that have a backup generator. The high level of harmonics is likely to cause the generator's voltage regulation to become unstable, ultimately resulting in the generator tripping offline to protect itself from damage. Scenario C (Figure 4) would be OK if the generator is oversized. Scenario D, which was all AFE drives in Figure 4, would be perfect for a generator.

Scenarios with generators become rather interesting when evaluating centralized mitigation approaches with active filters. Scenario E, if instead fed from a generator source in Figure 5, would allow the generator to function properly. However, Scenario F if instead fed from a generator source in Figure 5, is likely to result in the generator tripping offline unless the generator was significantly oversized. Engineers must take care in designing systems and considering those worst-case conditions, such as Scenario F. How can a Scenario F with generator power occur? One such situation:

- A lightning strike takes out the utility power
- That same lighting strike generates a power line transient that trips offline the active filter
- The active filter fault type is one that isn't auto resettable, thus the filter is no longer mitigating harmonics
- The generator engages and spins up to speed
- The automatic transfer switch transitions the facility load to the generator
- The harmonic loading causes voltage regulation issues and the generator becomes unstable
- The generator trips offline a short time later as it couldn't handle all the harmonic loading.
- The critical facility is without utility power and without generator power

Centralized mitigation best practices

The single point of failure, along with cost, are the two biggest challenges with a centralized mitigation strategy using active filters. There are ways to lower the risks associated with a single point of failure, however this does further increase the cost. Figure 8 reviews two different options to lower the chances of a single point of failure.

Option #1 in Figure 8 shows additional active filters throughout the system. The filters may or may not be sized to bring the THD_I levels down to 5%. Option #1 shows a scheme where active filter #2 and #3 cancels out over half of the drive's harmonics, and then active filter #1 cancels out the remainder to bring the facility to within IEEE 519-2014 compliance. In the event of any single filter failure or trip offline, there is still enough mitigation in the system from the other active filters to prevent significant harmonic concerns.

Option #2 in Figure 8 shows additional active filters in parallel. When a single active filter fails, or single smaller module within a large active filter fails, there is still other active filtration available. There is a concern if parallel active filters or modules share common components, such as a control power transformer (CPT), fuses, current transformer (CT), or power feed from the switch gear / panel, as now the single point of failure moved from the filter itself to an auxiliary component. And that auxiliary component becomes the new single point of failure. Designs should be implemented so there are no auxiliary single points of failure. Service should also be considered; if active filter #1 is down for service, it must be safely worked on from start to finish without impacting active filter #2.

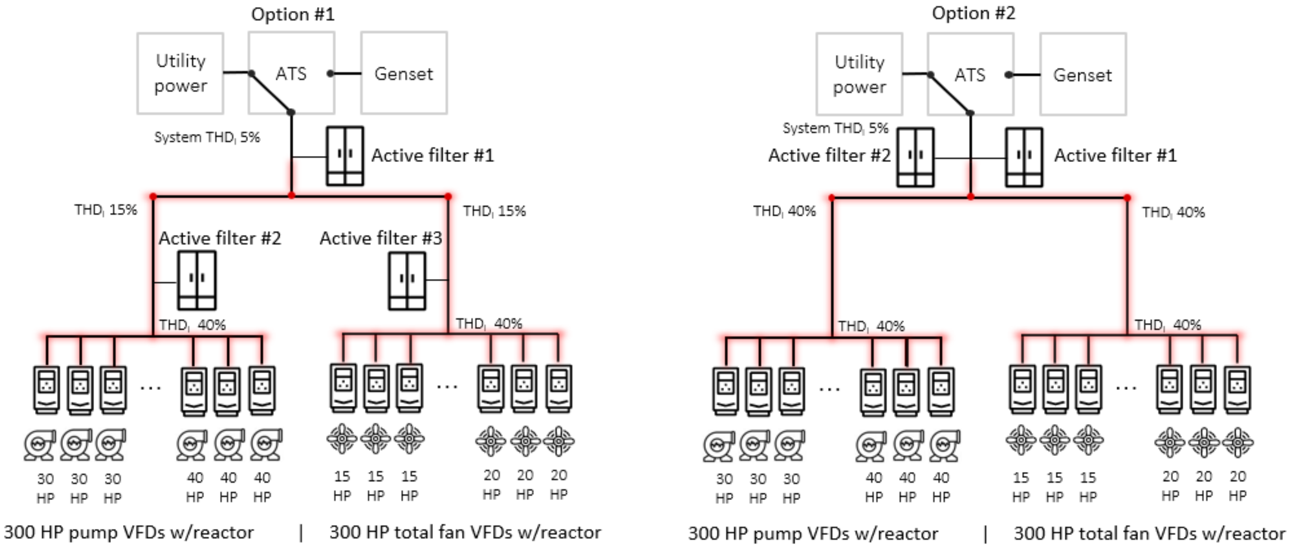


Figure 8 Centralize mitigation enhanced designs

Which to choose: Decentralized (AFE drive) or centralized (active filter) mitigation approaches?

There is rarely a one-size-fits-all solution, and the answer to this question is no exception. Each installation has its own unique attributes. However, in most cases, a decentralized approach, with the mitigation at the drive, is going to be the most reliable and lowest cost solution. Decentralized approaches do not have the single point of failure concerns. The topic of single point of failure is more critical for systems that require clean power or have backup generators. An AFE drive's decentralized approach has the mitigation integral to the drive, which eliminates any need to for additional equipment coordination. However, if an existing installation is failing IEEE 519-2014 and needs to be brought into compliance, and the only concern is IEEE 519-2014 compliance, then a centralized approach with an active filter is often the best solution.

Even though there is no one-size-fits-all solution that is best for every scenario, engineers naturally gravitate to one solution or another. This Technical Note 060 reviewed a lot of technical comparisons of one solution compared to another, but this document will leave those design engineers with a non-technical analogy, to find which solution they are most likely to gravitate to.

> Situation: You have a teenager in their bedroom with the music cranked up.
>
> Results: Everyone in your house is annoyed. Also, your windows are open, and in the past your neighbors have commented about the unpleasant music.
>
> You have two options:
>
> 1. Put on a pair of noise canceling headphones and shut your windows.
>
>   Or

2. Ask your teenager to turn down their music to an acceptable level.

What does each option (your answer) say about your feelings on decentralized versus centralized harmonic mitigation?

- If you went with option 1, then you are a centralized (active filter) kind of person. You aren't bother by the noise, and the windows are shut so neither are your neighbors. However, that noise is still in your house, which leaves other family members bothered by it.
- If you went with option 2, then you are a decentralized (AFE drive) kind of person. You prefer to stop the excess noise from being generated in the first place. Not to mention your solution is a little bit more efficient, as you stopped wasting the electricity on a maxed out stereo receiver.