HARMONIC MITIGATION CHALLENGES IN UNCONVENTIONAL ESP APPLICATIONS

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INTRODUCTION

Permian oil producers are facing increasing pressure from electric utilities to reduce power system harmonics, and the consequences for non-compliance can be severe. This paper details the results of a field-scale effort to reduce harmonics for a Champion X customer in the Permian basin, and how proper application and troubleshooting of harmonic filters exceeded the customer's and utility's goals.

BACKGROUND

Electric utilities have long understood that variable speed drives (VSDs) are a significant source of harmonic distortion on the power grid. However, distortion limits generally have not been imposed on oil producers because utilities have not been significantly impacted, until now.

Due to the large number of VSDs currently operating in the Permian basin (predominantly 6-pulse drives), the harmonics problem for utilities has reached a tipping point. In some locations, distortion of the power grid has become so severe that utilities are no longer able to communicate with smart metering devices – such devices are essential for utility billing – and loss of communication with even one of these devices is a serious issue. As a result, Permian basin utilities have begun mandating harmonic distortion limits, as well as setting deadlines to complete harmonic remediation work. Failure to meet the utility mandates can result in severe consequences for oil producers, including disconnection of electric service or heavy penalties.

In late 2018, a Champion X customer was contacted by their electric utility (OnCor Electric) and asked to reduce system harmonic distortion in various fields. Subsequently, the producer and the utility reached an agreement calling for a 10% harmonic current distortion limit and a timeline for remediation work. Though the customer took steps to reduce harmonic distortion, the project was not successfully implemented in the agreed timeframe – consequently, the utility issued a service disconnect notice. At this point the customer contacted Champion X for emergency assistance.

PROJECT CHALLENGES

Concurrent with the initial negotiation with the utility, the customer had engaged Champion X regarding a harmonic reduction strategy and had begun deploying passive harmonic filters for use with Champion X VSDs (approximately 100 filters were deployed in total). However, though filters had been *delivered* to various locations, it was discovered that roughly half had not been *installed*. In addition, of the filters that had been installed, a large percentage had some type of operational issue preventing the equipment from working effectively. The filter issues observed in the field can be summarized as follows:

- Wrong filter delivered to location
- Filter was not sized appropriately for the application
- Filter was not wired correctly
- Filter had a failed component (preventing proper operation)

Each of the above issues negatively affected filter harmonic performance – the result being that even though many filters had been deployed, harmonics were not significantly reduced in the customer's field. Though the customer had largely agreed on a harmonic reduction strategy using passive harmonic filters, many field sites were still employing active front end (AFE) VSDs or multi-pulse VSD/phase-shift transformer solutions. In addition, most customer well sites had a mix of various vendors' surface equipment installed, all of which were contributing to the overall harmonics issue – this presented some unique challenges for a system-wide harmonic reduction effort:

1. Harmonic remediation on competitor equipment is not always possible. An AFE VSD, for example, does not effectively reduce harmonics in an environment with poor power quality (most well sites fall under this category). In this case, not much can be done other than replace the equipment with a more effective method of harmonic mitigation – something the customer is often unable or unwilling to do.
2. Harmonics have a cumulative (additive) effect on the power system – i.e. each VSD contributes a piece of the total problem. On a well pad with a mix of equipment installed, remediating harmonics issues on Champion X drives is only part of the solution. In order to effectively mitigate harmonics in a given area, every piece of harmonic producing equipment must be dealt with.

See **Table 1** for a summary of the pros and cons of various harmonic mitigation methods. Due to the relative ease of installation and low cost of implementation, Champion X preferred solution is the passive harmonic filter.

SUMMARY OF PROJECT CHALLENGES

The challenges faced in this project are relatively common and can be generalized and applied to any modern oil field harmonic mitigation project:

1. The mitigation method selected must be proven to perform well in the customer's application environment (keeping in mind that oil wells change over time)
2. Proper installation of the equipment must be verified by some means
3. Proper operation must be regularly checked in order to ensure equipment continues to meet the customer and utility harmonic goals
4. Equipment repair must be addressed as needed (in a timely manner), in order to maintain harmonic compliance

PRACTICAL METHODS FOR ACHIEVING IEEE and IEC HARMONIC COMPLIANCE

All Champion X equipment involved in this project were being served by one utility substation. While this is certainly not a requirement for effective harmonic mitigation, it is noteworthy simply because (for this project) having all the affected equipment on the same sub-station circuit facilitated the work performed. In fact, the supplying utility mandated harmonic limits for each substation circuit individually. In this instance, the utility and customer agreed to limit harmonic current distortion to no more than 10% iTHD on average, *as measured at the substation*.

In order to ensure that 10% average current distortion (or less) was achieved at the utility substation, it is intuitive that individual loads should have some form of harmonic mitigation that could consistently perform at *less than* 10% THD – this could be considered an engineering 'rule of thumb' for this particular project. While there will naturally be some attenuation of harmonic currents and voltages in the power distribution circuit - from the point of harmonic production, to the point of measurement at the utility substation (which may be several miles away) – in specifying harmonic mitigation equipment that could consistently achieve less than 10% iTHD (even under challenging application conditions) Champion X could be assured that the average iTHD measurement at the utility substation would, in fact, be less than 10%.

This is noteworthy because the utility mandate automatically ruled out certain harmonic mitigation methods. For example:

- 12 pulse VSD/phase shift transformer solutions cannot be assured to achieve less than 12% iTHD even under optimal conditions.
- Likewise, AFE technology cannot be relied upon to achieve less than 10% iTHD in a typical oil field power quality environment (containing high voltage distortion levels in excess of 5%, in addition to frequent voltage imbalances in the system).

Harmonic mitigation projects are most effective if all the harmonic producing loads on an entire substation circuit are addressed – every harmonic producing load contributes a piece of the problem, thus, the most effective overall reduction strategy is remediating every harmonic load (by one means or another). This could mean addressing each load individually or installing a custom built large-scale harmonic filter at the utility substation, thus remediating the total harmonic load at one common point. However, depending on the situation, a 'piecemeal' approach to harmonic mitigation may be the only practical approach. Lack of access or inability (or unwillingness) on the part of the customer to properly remediate some types of harmonic loads is an example of one type of obstacle that may be encountered. *For example: if the customer paid for expensive, but ultimately ineffective AFE VSDs, they may be reluctant to incur additional expenses for new/better equipment that could actually fix the issue*.

In situations where there are multiple, different oil producing customers interspersed throughout a given sub-station service area, only cleaning up one particular customers harmonic problem (even if multiple sites are remediated) may not necessarily totally remediate the issue for the utility – other customers are also contributing to the problem. It's for this reason that the IEEE 519 standard contains limits on current "TDD" as opposed to "THD". THD is typically a 'snapshot' or instantaneous measurement of harmonic current distortion, while a measurement of TDD (by definition) may encompass multiple harmonic producing loads peak demand, at a point common to those loads. It is also noteworthy that the supplying utility in this project did not hold the customer accountable to the most strict iTDD category of the IEEE 519 standard. This represents a practical understanding (on the part of the utility) regarding the real-world limitations on certain methods of harmonic mitigation technology. The 10% average iTHD mandate was an acknowledgment that many customers often face a daunting task regarding harmonic mitigation, and not all factors are in their control. See **Table 2** for the IEEE-519 2014 current distortion limits.

Modern utilities with an understanding of harmonic mitigation technology may give customers some flexibility with regard to the IEEE 519 standard (i.e. not requiring compliance with the most restrictive categories of the IEEE standard) – however, it is still important for the specifying engineer to be aware of the IEEE recommendations, as not all utilities may be so accommodating. In addition, the specifying engineer should have realistic expectations about what different types of harmonic mitigation technology can actually achieve, given the challenging application environments most oil fields represent.

FIELD FINDINGS AND OBSERVATIONS

In July 2019, Champion X performed a field survey of select customer locations. In order to achieve the greatest harmonic reduction impact, a field was identified that was populated with 100% Champion X equipment. Initial surveys of the field confirmed that harmonic levels were high, ranging from 15-65% iTHD, which is typical of a field predominantly comprised of 6-pulse drives with little to no harmonic mitigation (see **Figure 2** and **Table 3** for data and observations from initial survey):

- The field was comprised of 22 Champion X VSDs: 21 6-pulse drives and one AFE
- 5 VSDs had filters already installed, only two of which were operable
- The remaining 3 filters were either inoperable or inappropriately sized for the application
- Current distortion levels ranged from 15-65% THD
- Field voltage distortion levels were also quite high (in the range of 7-8% VTHD)

Voltage distortion is notable because passive filters perform optimally when VTHD levels are 5% or less. This finding not only demonstrated the scope and magnitude of the harmonics issue, but further emphasized the need for a system-wide harmonic remediation effort. A single passive harmonic filter installed in such an environment, even if appropriately sized, has a limited impact towards achieving the utility and customer goals – this is demonstrated by the performance of the filters installed at 4006LS and 4008LS in **Table 3** and **Figure 3**.

Given the initial survey results, the Champion X team focused its efforts (Phase 1) on progressively improving power quality in the field by executing the following steps:

1. Applying harmonic filters to the largest amperage loads first (beginning with wells 4002LS-4008LS)
2. Sizing filters based on the following guideline (considering pre-existing VTHD levels): Filters should be sized 40% larger than the 4-week (historical) average amp load
3. Following completion of Phase 1, re-evaluate and apply filters to the remaining sites as necessary until customer and utility goals are met

Note that two of the four wells surveyed in Phase 1 (**Figure 3**) previously had harmonic filters installed, though the iTHD performance was not in compliance with the customer or utility goal of 10%. This poor filter performance was a direct result of the high-voltage distortion in the field. Though ultimately the Phase 1 results showed an improvement in power quality, it was evident that expanding the harmonic remediation effort to the remaining well sites was necessary to achieve customer and utility goals.

Phase 2 of the project involved the following steps:

1. Analyze the remaining 18 well sites to appropriately size filters for these locations
2. Supervise the filter installations to ensure they were delivered and wired correctly
3. Remove/replace or repair equipment that was not functioning properly
4. Re-evaluate power quality and document improvement

As can be seen in **Figure 4**, **Figure 5** and **Table 4**, Phase 2 yielded a dramatic reduction in field voltage distortion and a corresponding improvement in the performance of individual filters at each well site. The iTHD reduction at each site in many cases exceeded the utility mandate, while the harmonic reduction at the substation far exceeded the utility and customer goals – dropping from initial values of 25-30% iTHD to 3-7% iTHD.

NEW TECHNOLOGY

The observations regarding real world equipment performance and also the challenges evident in this project spurred product improvements and new development. While the results obtained with passive filters was excellent overall, one downside of this technology is that the mitigation performance varies with load. Specifically, as the electrical loading of ESP pumps/motors *declines,* filter mitigation efficacy *also declines* (see **Figure 6**).

The performance graph shown in **Figure 6** demonstrates the decline in harmonic mitigation efficacy for a single passive filter as the electrical loading declines. Note that IEEE 519 thresholds for iTDD are overlaid on the single filter performance graph, and demonstrate the approximate electrical loading levels where (under ideal lab conditions) the IEEE harmonic thresholds are violated. Considering application environments with severe background voltage distortion levels, the harmonic mitigation performance of a single filter will be further degraded (performance worsens) compared to what is observed in ideal conditions.

In unconventional ESP applications this decline in electrical load is quite typical – equipment that is loaded to 100% of its electrical rating at the outset of the production period, may only be loaded to 40% in as little as six months later in the production cycle. It's quite possible that a wellsite that started out in compliance with customer and utility harmonic goals will no longer be compliant as the well matures and production declines. At this point the customer is faced with a choice:

- Continue to operate with higher harmonic levels (possibly incurring utility penalties)
- Change out equipment (downsize the harmonic filter) in order to achieve better performance and continued compliance

Recognizing this dilemma, Champion X developed and deployed a "dual-stage" passive filter architecture - incorporating two 'single stage' (smaller) filters into one enclosure. This design capitalizes on the key concept that single stage filters have better harmonic performance the greater the electrical load. The dual-stage filter design dynamically switches IN or OUT a single passive filter stage as the electrical loading level changes. The result is better overall harmonic reduction performance over a wider range of load than a stand-alone single stage filter (see **Figure 7**).

In addition to filter architecture improvements, each dual-stage filter is equipped with a power quality monitoring device. This device allows for remote monitoring of filter performance, not only ensuring continued harmonic compliance but also triggering alerts if the filter needs repair (**Figure 8**). With tools like remote power quality monitoring, an alarm in the VSD can be triggered when harmonic distortion levels exceed customer thresholds and equipment needs attention. Based on interpretation of the power quality waveform, the filter can be remotely diagnosed by knowledgeable engineering staff, prompting a technician visit for repair.

Prior to this technology, the customer would only be alerted to an equipment performance issue if a technician visited the site and physically checked the equipment, or if the utility contacted the customer directly to report harmonics violations. Given the above, it’s clear that remote power monitors are vital in the modern oil field and have a myriad of potential applications:

- Remote troubleshooting of many different types of equipment (VSDs, phase-shift transformers, passive filters, motors)
- Data from damaging power events can be used in forensic/failure analysis (lightning strikes, surges, sags, etc.)
- Real-time equipment “health” monitoring ensures that the customer is always in compliance with harmonic standards
- Immediate alerts if repairs are required

CONCLUSION

Based on the field work performed during this project, the following guidelines and recommendations were developed for future filter applications in oilfield environments:

1. All VSDs must have some form of harmonic mitigation in place to have a significant impact on customer distortion levels. In regions such as the Permian, VSDs with passive filters should be the standard offering (in environments with poor power quality, passive filters are the superior harmonic solution).
2. Voltage distortion must be considered before filters are applied. If pre-existing VTHD levels are greater than 5%, the filter must be sized 40% larger than the 4-week historical average amp load. For environments with less than 5% VTHD, filters should be sized 25% larger than the 4-week historical average amps (or anticipated amperage load in the case of a new installation).
3. In unconventional ESP applications a dual-stage filter architecture is highly recommended.
4. Filter operation and wiring must be verified on start-up with a power quality meter.
5. Filter applications should be properly protected with surge protection devices – a ‘tiered’ approach to surge protection is most desirable – i.e. surge protection at the service entrance, at the filter, and at the VSD.
6. Continued operation of the filter and filter surge protection should be monitored – this can be accomplished with SCADA monitoring services, and remote power quality monitoring services.

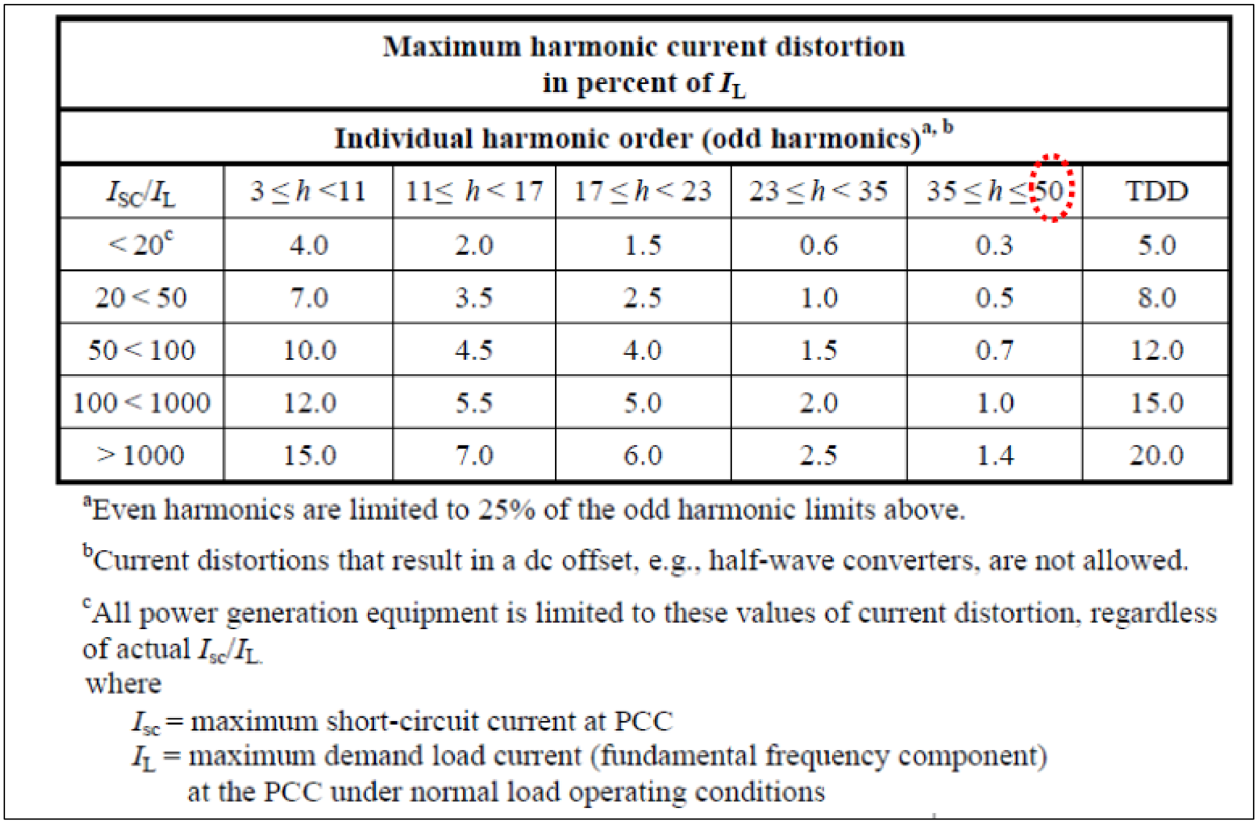
REFERENCES

IEEE Std 519 – 2014, “IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems”

Table 1. *Comparison of harmonic mitigation methods*

Equipment	Pros	Cons
Active front end VSD	Performance can be excellent, provided the VSD operates in a stable, low-noise environment.	Performance quickly degrades in poor quality / oilfield-type environments. This can prevent IEEE harmonic compliance.
		The high cost of equipment.
12 or 24 pulse VSD/phase-shift	Performs reasonably well provided equipment loading is high and current balancing of converters is managed (though this solution still does not often comply with IEEE guidelines)	Performance is highly dependent on equipment loading and power system stability. Must be loaded to ~80% of rating to achieve good performance.
	Phase-shift transformer is simple and robust and generally has a long life.	The high cost of equipment and installation.
Passive harmonic filter	Performance is excellent over a wide range of loads. Can comply with and even exceed IEEE guidelines.	Extra care must be taken in equipment sizing and application.
	Low cost	Shorter lifespan than phase-shift solutions – may require periodic field repairs.

Table 2. *IEEE Standard 519-2014; current distortion limits for systems rated 120V through 69V*



Maximum harmonic current distortion in percent of I_L						
	Individual harmonic order (odd harmonics)[a, b]					
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a] Even harmonics are limited to 25% of the odd harmonic limits above.

[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c] All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where

I_{sc} = maximum short-circuit current at PCC

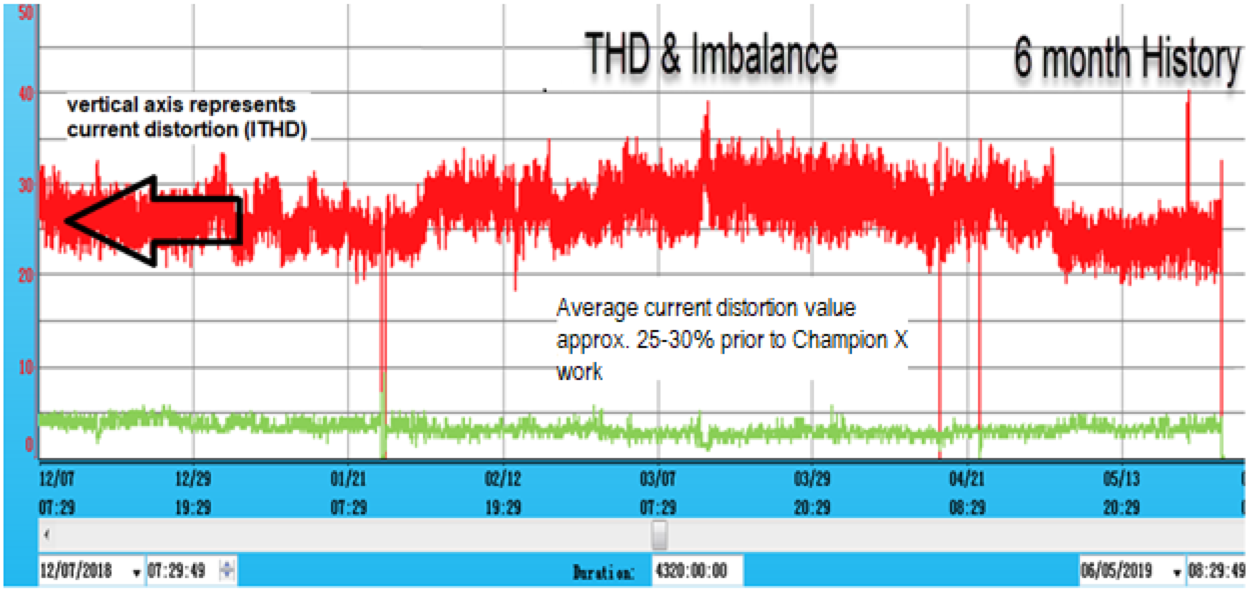
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

***Table 3**. Summary of initial power quality survey*

Well Name	Filter?	ITHD	VTHD
4002LS	No	>35%	>7.9%
4004LS	No	>35%	>7.9%
4006LS	482 amp	15.6%	7.6%
4008LS	482 amp	17.7%	7.4%
3901LS	No	40.3%	7.5%
3906LS	No	40.4%	7.8%
3904LS	No	56.7%	7.8%
3902LS	No	34.4%	7.9%
2306LS	320 amp (oversized)	25.7%	7.3%
2308LS	No	50.2%	7.6%
2202LS	No	35.5%	7.8%
2202H	AFE (malfunctioning)	23%	5.9%
2304LS	No	33.3%	7.7%
2302LS	636 amp (oversized)	31.6%	6.8%
2201LS	No	30.2%	7.5%
2307 LS	No	31.1%	8.3%
2305LS	No	35.5%	8.1%
2303LS	No	N/A	N/A
4001LS	No	55.2%	7.6%
4003LS	TCI filter (inoperable)	39.5%	7.6%
4002H	No	65.5%	8.1%
4004H	No	35.7%	7.8%

***Table 4:** Summary of field results*

		BEFORE			AFTER	
Well Name	Filter?	ITHD	VTHD	Filter Installed	ITHD	VTHD
4002LS	No	>35%	>7.9%	482 amp	9.1%	4.6%
4004LS	No	>35%	>7.9%	482 amp	7.9%	4.4%
4006LS	482 amp	15.6%	7.6%	482 amp	7.8%	4.3%
4008LS	482 amp	17.7%	7.4%	482 amp	10.3%	4.4%
3901LS	No	40.3%	7.5%	240 amp	15%	4.4%
3906LS	No	40.4%	7.8%	320 amp	26,6%	4.4%
3904LS	No	56.7%	7.8%	240 amp	15.4%	4.6%
3902LS	No	34.4%	7.9%	240 amp	7.9%	4.6%
2306LS	320 amp (oversized)	25.7%	7.3%	240 amp	9.4%	4.9%
2308LS	No	50.2%	7.6%	240 amp	8.5%	5.1%
2202LS	No	35.5%	7.8%	240 amp	17.1%	4.8%
2202H	AFE (malfunctioning)	23.0%	5.9%	320 amp	9.8%	5.0%
2304LS	No	33.3%	7.7%	240 amp	12.6%	4.9%
2302LS	636 amp (oversized)	31.6%	6.8%	240 amp	10.4%	4.9%
2201LS	No	30.2%	7.5%	320 amp	10.5%	4.3%
2307 LS	No	31.1%	8.3%	320 amp	14.3%	4.7%
2305LS	No	35.5%	8.1%	320 amp	10.1%	4.3%
2303LS	No	N/A	N/A	320 amp	22.1%	4.3%
4001LS	No	55.2%	7.6%	240 amp	8.8%	4.7%
4003LS	TCI filter (inoperable)	39.5%	7.6%	240 amp	14.2%	4.5%
4002H	No	65.5%	8.1%	240 amp	8.2%	5.0%
4004H	No	35.7%	7.8%	240 amp	10.5%	4.5%



vertical axis represents current distortion (ITHD)

Average current distortion value approx. 25-30% prior to Champion X work

Figure 1. *The above recording was provided to UNBRIDLED ESP Systems prior to the field work and represents current distortion levels measured at a utility substation which served the well sites involved in this study. Note that iTHD values were 25-30% on average, while the customer and utility targets mandated no more than 10% iTHD on average.*

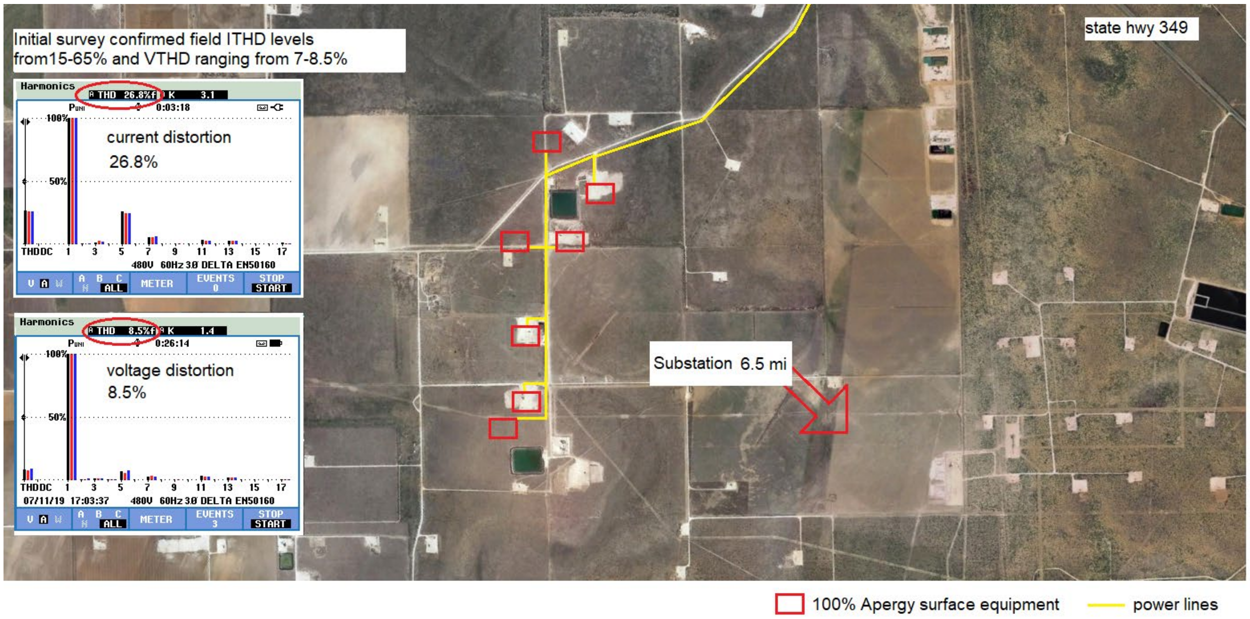
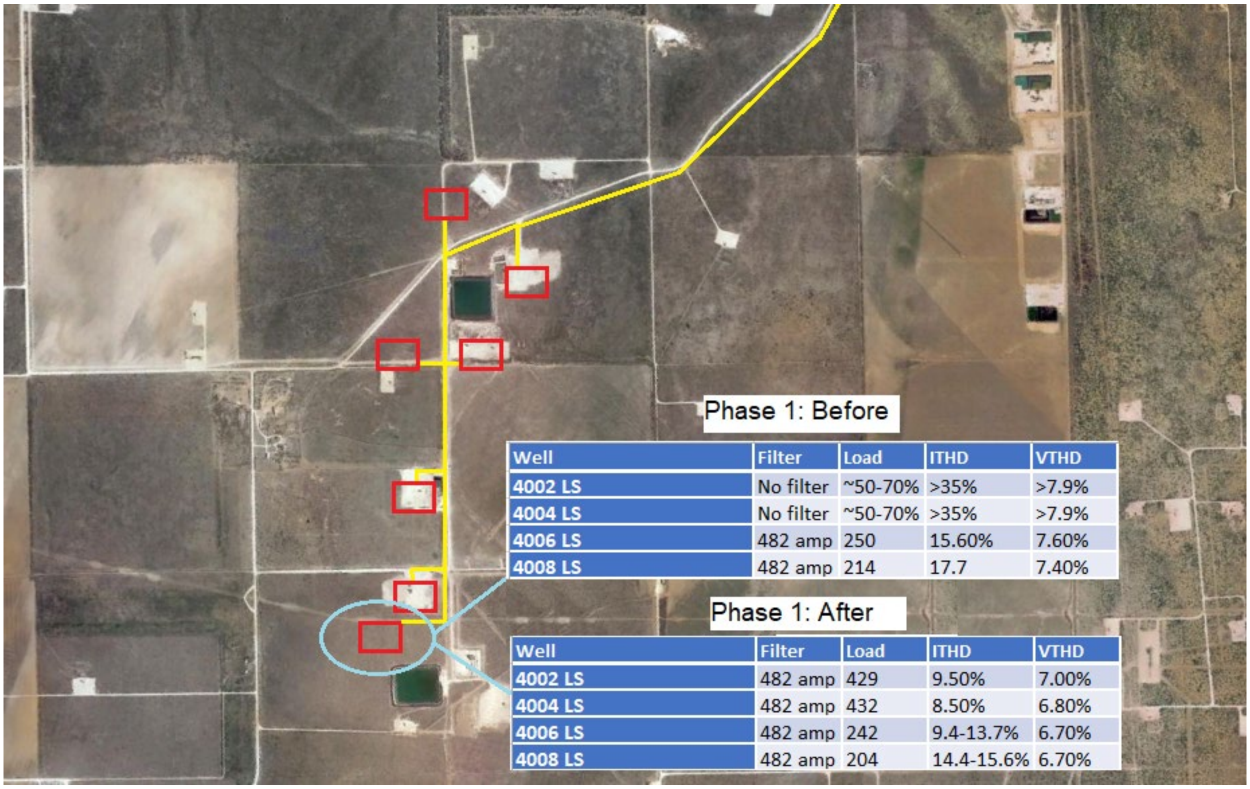

Initial survey confirmed field ITHD levels from15-65% and VTHD ranging from 7-8.5%

__Figure 2.__ Initial survey of field confirming high current and voltage distortion

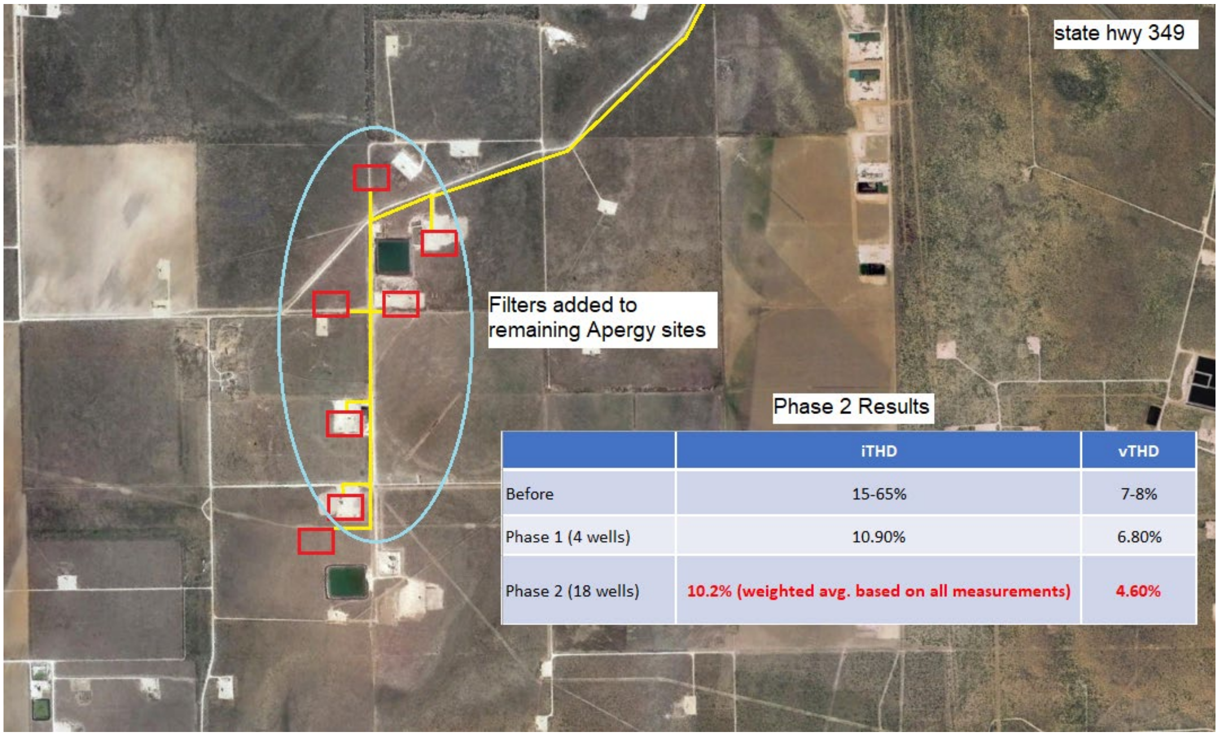

Phase 1: Before

Well	Filter	Load	ITHD	VTHD
4002 LS	No filter	~50-70%	>35%	>7.9%
4004 LS	No filter	~50-70%	>35%	>7.9%
4006 LS	482 amp	250	15.60%	7.60%
4008 LS	482 amp	214	17.7	7.40%

Phase 1: After

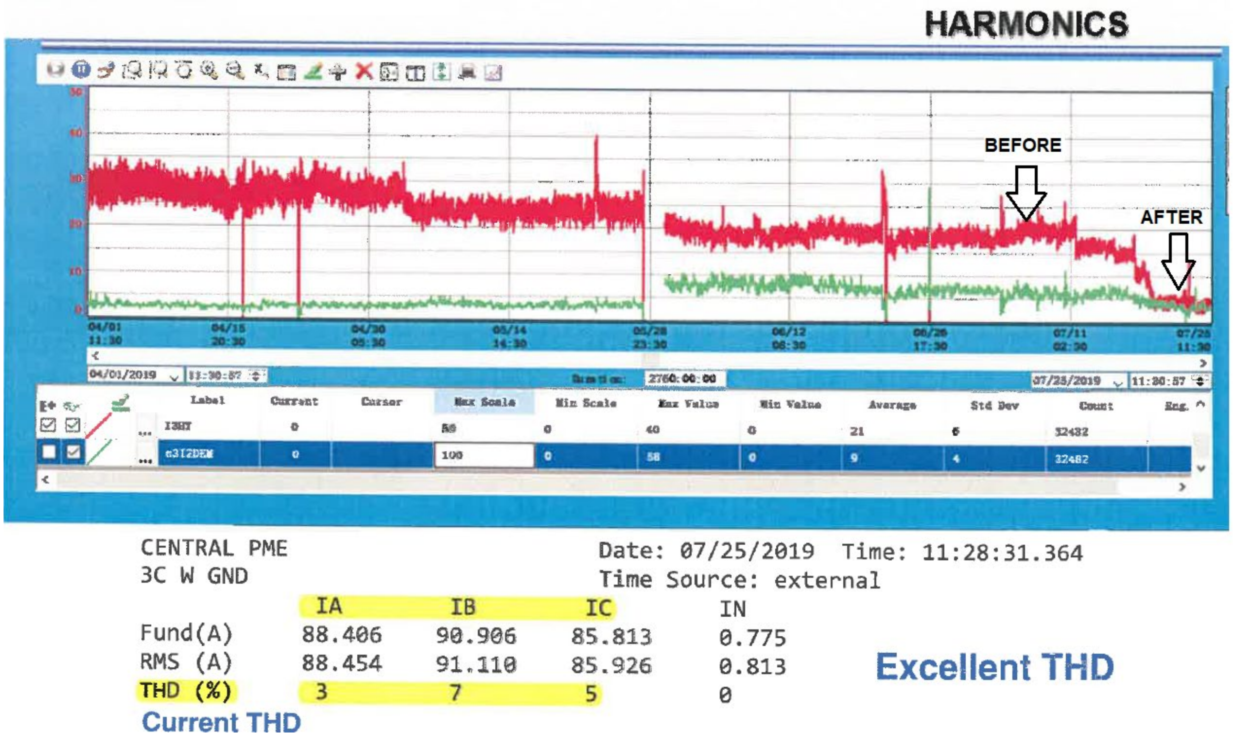
Well	Filter	Load	ITHD	VTHD
4002 LS	482 amp	429	9.50%	7.00%
4004 LS	482 amp	432	8.50%	6.80%
4006 LS	482 amp	242	9.4-13.7%	6.70%
4008 LS	482 amp	204	14.4-15.6%	6.70%

__Figure 3.__ ‘Phase 1’ target wells (4002-4008LS)



	iTHD	vTHD
Before	15-65%	7-8%
Phase 1 (4 wells)	10.90%	6.80%
Phase 2 (18 wells)	10.2% (weighted avg. based on all measurements)	4.60%

Figure 4. *Progressively adding 18 filters to the remaining sites resulted in a dramatic reduction in current and voltage distortion – exceeding customer and utility goals*



		Label	Current	Cursor	Max Scale	Min Scale	Max Value	Min Value	Average	Std Dev	Count	Eng.
☑	☑	I3HT	0		50	0	40	0	21	6	32432	
☐	☑	n3I2DEM	0		100	0	58	0	9	4	32482	

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CENTRAL PME                              Date: 07/25/2019  Time: 11:28:31.364
3C W GND                                 Time Source: external
                IA          IB          IC          IN
Fund(A)     88.406      90.906      85.813       0.775
RMS  (A)    88.454      91.110      85.926       0.813
THD  (%)     3           7           5           0
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Excellent THD

Current THD

Figure 5. *Harmonic reduction at the substation was well below utility mandated 10% iTHD*

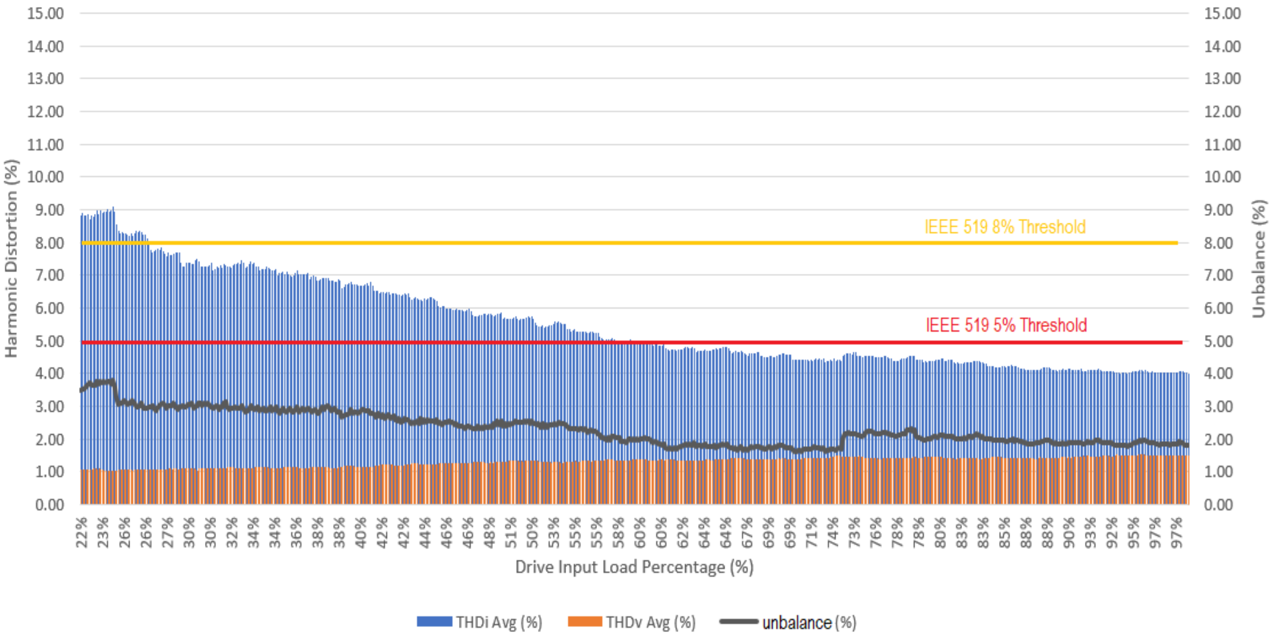


***Figure 6**: Typical performance of 'single stage' passive harmonic filter*

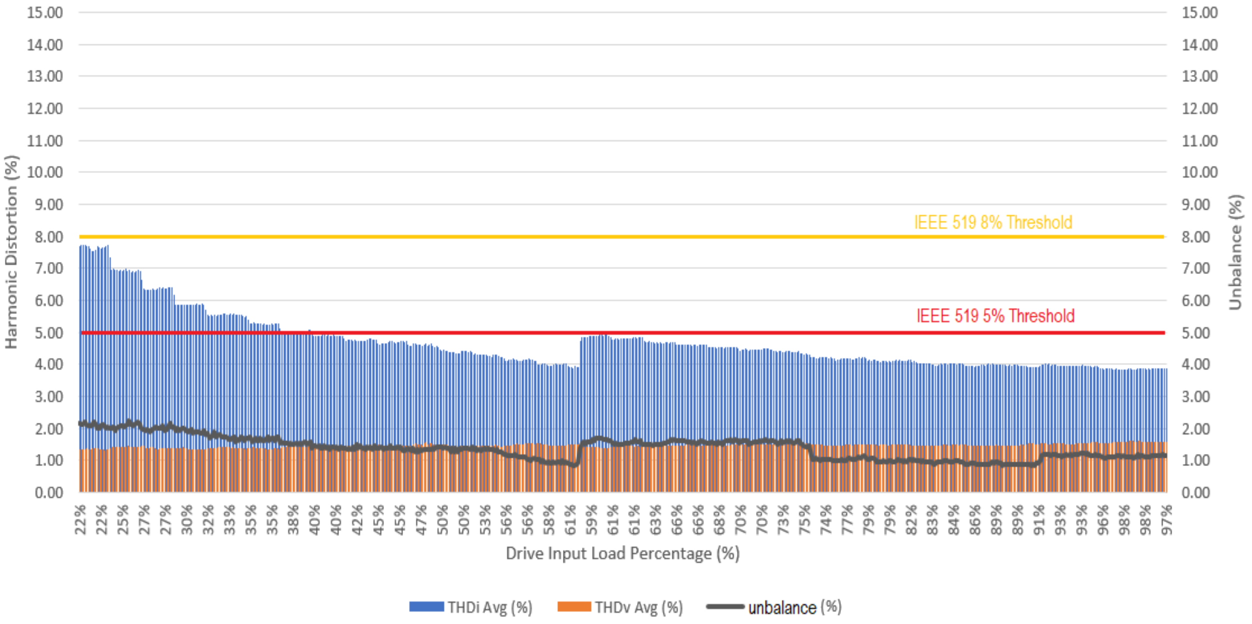
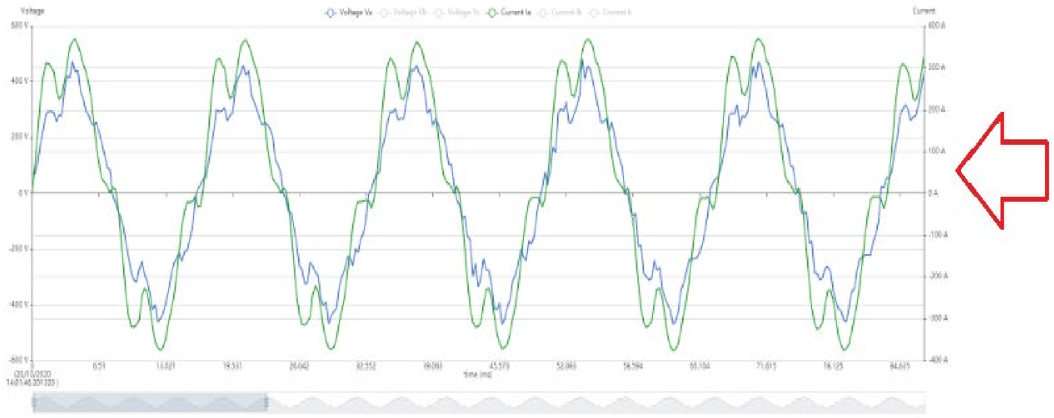


***Figure 7**: 'Dual stage' passive harmonic filter performance improves upon single stage performance*



waveform indicates a filter component problem

***Figure 8**: Remote power quality monitoring facilitates equipment troubleshooting*