OIL FIELD HARMONIC CONCERNS RESULTING FROM HIGH IMPEDANCE SOURCES, MULTIPLE POWER CONVERTERS AND LONG CABLES

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Paper No. PCIC-08-121

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Abstract—The paper presents an effective, robust and economical design solution for a severe power system harmonic problem. The case study examines an isolated power system at an oil field central processing facility supplied by on-site generators. Elevated harmonic distortion originates from the electronic adjustable speed drives installed on the well site submersible pump motors. The original design uses phase shifting techniques that achieve a significant reduction in harmonic current. Unexpectedly, even though harmonic current remained moderate, harmonic voltage distortion became excessive as the system grew in size. This unusual condition arose from a combination of high source impedance and distributed stray capacitances from long power cables that created many partial resonances throughout the system. Voltage distortion contributed to extensive equipment failures and system upsets over the years. The implemented solution is expected to provide considerable long-term improvement in the power system operation and availability.

Index Terms — harmonic analysis, harmonic filter design, partial resonance, high impedance sources, phase shifting, distributed capacitance.

I. INTRODUCTION

This case study examines the harmonic problems and presents a solution for a stand-alone isolated power system supplied by diesel and gas turbine generators. There are several hundred electronic motor drives used to power oil well submersible pumps. Measurements taken at the facility site show very high voltage harmonic distortion levels, exceeding industry accepted IEEE Standard 519 limits by as much as 600% in some locations. The voltage distortion at the electronic Adjustable Speed Drive (ASD) terminals was typically over 30% Total Harmonic Distortion (THD). At the main generator terminals distortion reached 8% - extremely high for these critical and sensitive power system components. Current distortion in comparison was relatively moderate - between 7% and 27%.

Harmonic analysis uses a mathematical model of the power system to examine harmonic disturbances. Effort was expended to carefully model frequency dependent details that are of importance for the harmonic analysis unique to this system.

The paper also outlines some important design considerations for large industrial power system harmonic filters.

II. SYSTEM DESCRIPTION

The electrical generation system consists of 18 diesel generators, distributed across 3 13.8 kV buses and 2 gas turbine generators on a separate 13.8 kV bus. The system output is approximately 60 MW. Refer to Fig. 1 for a simplified single line diagram of the system.

III. GENERAL HARMONIC FILTER DESIGN CHALLENGES AND IMPORTANT CONSIDERATIONS

The primary purpose of a harmonic filter design is to ensure reliable operation of the power system and compliance with the energy supply utility and/or industry standard harmonic levels [1]. A power system harmonic filter is also usually used for reactive power compensation and voltage support. It typically improves power factor at the point of common coupling (PCC) with a utility grid. Industrial customers are encouraged to maintain a minimum power factor at the PCC of between 0.9 and unity (depending on the jurisdiction) or else economic penalty factors are applied.

Each harmonic filter design is specially designed for the environment where it is deployed. What makes them so unique? Present day power systems frequently contain many more harmonic sources, as well as nonlinear and capacitive elements that interact with the inductive and resistive components traditionally found in power systems. It is almost impossible to install a large harmonic filter (> 1 MVAR) “off the shelf” at a certain locations and expect harmonic problems to be mitigated correctly. The harmonic filter is an intricate subsystem that consists of elements (reactors, capacitors and resistors) combined to interact in a prescribed way within the power system. This paper attempts to describe the core features of and major challenges inherent in harmonic filter design.

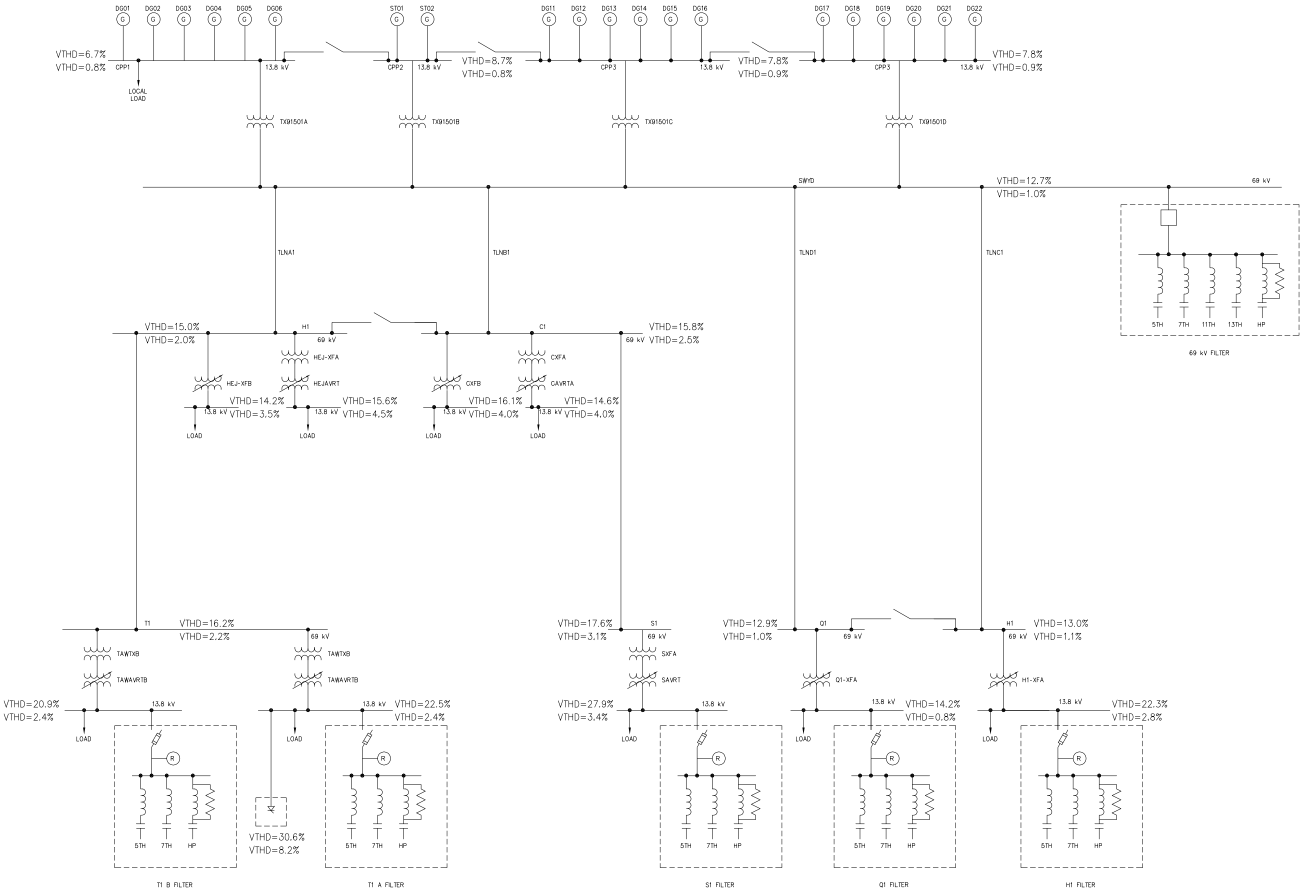


Fig. 1 Single Line Diagram

A) Three common industrial configurations requiring harmonic mitigation

To demonstrate some of the challenges, we will compare the different harmonic filter design approaches of three common types of industrial configurations that require large harmonic filter/power factor correction systems (1 MVAR to 100 MVAR).The power system operating conditions are a crucial element to be considered during design:

i. A plant power system connected to a utility grid, with 1 or 2 large harmonic loads in the 1-20 MW range (e.g., an electrochemical plant with 2 parallel processes and 2 power converters).
ii. A plant power system connected to a utility grid, with up to 10 harmonic loads and with energy consumption in a range of 200 MW (e.g., a large electrochemical plant).
iii. A stand-alone isolated power system, with a large number of widely dispersed harmonic loads (the subject of this paper.)

B) A number of harmonic loads, mutual interference and location

The quantity of harmonic loads has a major impact on the harmonic filter design. In case (i), it can be problematic due to the large size (i.e., "off the shelf" designs are still not appropriate) but relatively straightforward.

Note: It has been the authors' experience that with smaller harmonic loads and filters, minor errors in design, manufacture or implementation are often masked by the relatively low impedance of the power system and do not become an issue. As the power level increases, accuracy of detail becomes more important—simply scaling up a design can lead to problems.

In the case of multiple large harmonic loads (~10), the problem becomes more complex. Often, each harmonic filter is matched to a power converter (harmonic load). In practice, these systems build up over time. As the plant expands, one must take special care to ensure that all harmonic loads, harmonic filters, and system impedances interact appropriately without deleterious effects. Adding additional filters and harmonic loads requires a precise examination of all the possible operating combinations to avoid potential amplification and account for any pre-existing resonances at the design stage. Special consideration is required in cases where two or more power converter/harmonic filter pairs are fed through the same transformer and connected to a common bus. In this case, a detailed analysis of possible resonance between harmonic filters is necessary, since inter-filter resonance can be a challenge to solve when both filters have the same tuning point.

The third type of system is one consisting of many harmonic loads, widely dispersed over a large network. In the case study for this paper, there are several hundred electronic ASDs in the 200 kW to 1 MW range. These types of systems typically grow over a number of years, starting with a smaller number of harmonic loads. Since the harmonic currents produced by these loads influence the power system via ohms law at the respective harmonic frequencies:

$$V_{harmonic} = I_{harmonic} \times Z_{harmonic} \qquad (1)$$

It follows that a large system will have negligible harmonic problems with a small number of loads, becoming increasingly problematic as the number of harmonic loads increases.

The subject case is an isolated system with no regulatory penalty for harmonic distortion content in voltage/current. However, as the system expanded with additional harmonic loads, operational problems became more prevalent due to the increased voltage distortion in the system. Another significant factor is that the additional capacitive and nonlinear elements gradually added to the system can develop partial resonances that drastically increase voltage distortion. This paper provides examples of the levels that voltage harmonic distortion can reach due to these partial resonance conditions.

C) Economics

Financial considerations can significantly influence filter design. Ideally, each harmonic source is paired with an appropriate harmonic filter that would absorb all harmonic currents generated at the load. Filtering low voltage drives was applied earlier in the project with fewer ASDs. These filters were installed between the step-down transformer and the drive. Although effective, the low voltage, high current filters were costly both in terms of the capital cost of the filter and in installation costs due to the high ampacity cabling required. The few individual filters became ineffective and were removed as the system grew.

Another important cost factor is the number of capacitors used for a filter design. In large filters (>10 MVAR), it is always more cost effective to select larger capacitors of several hundred kVAR each to build up each harmonic filter element. This solution, however, may not apply to smaller filters, as there will not be sufficient contingency when individual capacitors fail to maintain the tuning effectiveness of the filter.

IV. SYSTEM PROBLEMS DUE TO HARMONIC INTERFERENCE

In a typical power system, excessive harmonic currents create elevated voltage distortion levels. Excessive voltage harmonic distortion in the power system has a detrimental effect on all electrical equipment in the system.

In this case study example, both field measurements and detailed analyses of the system demonstrate that at some buses there are even and other non-characteristic harmonics present. This is typical of large operating facilities. Malfunctioning ASDs or abnormalities in transformers, motors and other magnetic equipment generally creates these non-characteristic harmonics. Non-characteristic implies that they do not exist in an ideal system. As a result, harmonic solutions often do not address non-characteristic harmonic frequencies. References [8-11] provide detailed information on the theory behind the creation of even harmonics and a practical case study on mitigation.

In general, the following types of problems can develop when harmonics are present:

- Failures of components in ASDs and other electronic equipment
- Misoperation of communication in ASDs and other static converters
- Increased heating due to extra iron and copper losses in machines at the higher frequencies
- Shortened lifespan of insulating systems in rotating machinery and transformers
- Decreased machine efficiency and influences on developed torque
- Improper operation of control and monitoring equipment
- Fuse failures and nuisance tripping of circuit breakers
- Higher values of the voltage drop in the system caused by flow of the harmonic currents
- Cables involved in system resonances may be subjected to excessive voltage stress and corona, which can lead to dielectric (insulation) failure
- Positive and negative errors are possible in operation of metering and instrumentation with harmonic distortion present
- Increased losses in switchgear that will reduce steady-state current carrying capability
- Distortion factors above 10% will also cause problems with protective relays

For example, in this case study, site maintenance personnel experienced more ASD component failures with the increasing number of installed drives and higher harmonic voltage distortion levels.

V. POWER SYSTEM MODELING FOR HARMONIC ANALYSIS

The first step in the design of harmonic filters is to develop an accurate model of the power system and perform a thorough harmonic analysis of the system. Harmonic analysis uses a mathematical model of the elements in a power system in order to qualify and quantify harmonic sources and the impact on the power system. The analysis requires an understanding of harmonics generated by non-linear loads. Details of modeling power system elements are given in [2-7].

An acceptable model of the power system must yield approximately the same results as the field measurements. A strong correlation between field measurements of actual harmonic currents and voltages and harmonic load flow is crucial, especially with difficult pre-existing partial resonance situations. Even in the simple single harmonic filter case, an effort should be made to record existing harmonic flow in the plant. There is always the potential danger of missing alternative harmonic loads present in the plant.

Several commercial software packages may be used for harmonic analysis. In power system analysis, it is usual to model three-phase power systems as a single phase. In simple cases, single-phase representation of an industrial system is considered adequate since industrial systems are normally built as balanced systems. The software package usually consists of modules, specifically used for various analyses in industry, such as comprehensive AC load flow, DC load flow, short circuit analysis, protection and coordination, harmonic analysis, etc. However, to the authors' knowledge, none of the commercially available packages offer integrated and coupled analysis of AC and DC systems.

A mathematical model of de-coupled AC or DC systems is straightforward and components in general are adequately modeled. Software packages model loads as motor or non-motor loads. Each load may be modeled as a constant power, a constant current and a constant impedance type or combination. For AC analysis, the load representations are sufficiently accurate for decoupled systems (e.g., a transformer is modeled with its short circuit impedance and no load losses, etc.). However, integrated AC and DC analysis is imperative when the DC and AC sides strongly influence each other. The coupling of two systems is achieved through proper load models that represent power converter harmonic sources. Conversely, none of the load models described above properly reflect changes in DC load due to voltage fluctuations. In other words, the "model coupling" of two systems is not properly reflected through the load representations.

Special care should be taken when modeling a system with a large DC source, as substantial errors in sizing of harmonic filters may occur. AC power systems recognize the power converter (rectifier) as a load, characterized with a demand in real and reactive power with an appropriate power factor, independent of voltage. Rectifier operation, in turn depends on both incoming voltage and load fluctuations. This can create nonlinear impedance variations on the AC side and subsequent changes in current/voltage profiles. To compensate, the converter control system adjusts semi-conductor modulation. This directly impacts both the displacement and distortion power factor of the converter and leads to a different demand for the reactive power. As a result, modeling the total reactive power necessary to compensate the process accurately can require a substantial iterative effort.

Furthermore, the voltage supplied at the PCC itself varies. The variation in supplied voltage must be taken into account during load flow and harmonic analysis. It is critical to have all these variables in hand for a proper representation of the system to provide a "good enough" model of harmonic behavior. If the behavior of the model does not reflect the actual situation in large systems, with high harmonic rich power demand, the filter design can be oversized (or undersized) by more than 10% - 10 MVAR or more. Potential benefits in reactive power compensation could be lost, resulting in utility penalties and substantial wasted expenditures. To overcome this problem, procedures and custom software tools have been developed. In short, an acceptable harmonic analysis requires the correct characteristics of all significant harmonic loads.

ASDs are the most common type of harmonic load. They are the predominant nonlinear load used in oil field power systems. These drives typically have a rectifier front end, and one could model changes in power factor in the same manner as a large rectifier load. However, in most cases, these types of loads are much smaller in terms of active and reactive power and this level of detail is not required. Nevertheless, there are many topologies of drives and these loads require attention during the modeling process.

A vital step of every harmonic analysis model is the selection of a correct harmonic signature that represents the harmonic behavior of the load. For the existing systems, the most practical method is to record the field harmonic signature of the equipment, while for new units, the manufacturer can provide detailed spectrums for different loading conditions and power factors.

VI. HARMONIC FILTER DESIGN

This case study examines the harmonic problems and presents a solution for a stand-alone isolated power system supplied by diesel and gas turbine generators. The majority of the well pumps are supplied by low voltage ASDs with multi-tap step-up transformers to provide the required voltage level. The facility electrical power system generally consists of generators, cables, transmission lines, transformers and motors. For the purpose of this study, ASD driven motors are considered the only harmonic load.

Measurements taken at the facility site showed elevated harmonic distortion levels, exceeding industry accepted IEEE Standard 519 limits by as much as 600%. The total voltage distortion at the ASD terminals was over 30%. The generators' terminal voltage distortion reached 8% – too high for these critical and sensitive power system components. Current distortion, in comparison, was relatively low, between 7% and 27%.

Initial efforts at modeling the system were unsuccessful, as there was not enough current distortion in the system with the general equipment impedances used in the model to develop the voltage distortion actually measured in the field. Efforts were redoubled to carefully model power system components, particularly any elements that added capacitance—with special attention paid to potential resonance conditions.

A) Power system modeling and harmonic analysis

Three types of drives are used, traditional SCR drives, hybrid transitor drives and the majority, (70%) IGBT drives. Each drive consists of two 6-pulse halves supplied by a 3-winding 30-degree phase shifting transformer that converts each 6-pulse drive pair into a quasi 12-pulse system, reducing harmonic currents. This approach has worked well, evidenced by the relatively low current distortion measured.

Each drive system is packaged in 1 drive cabinet and powers 1 well submersible pump motor. To aid the modeling and analysis process, each load is split into 2 halves and connected to a phase shifting transformer in the model. In this way, it was possible to correlate the model to the recorded harmonic readings taken on each half of the drive using the harmonic signatures of the drives.

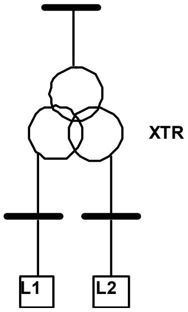
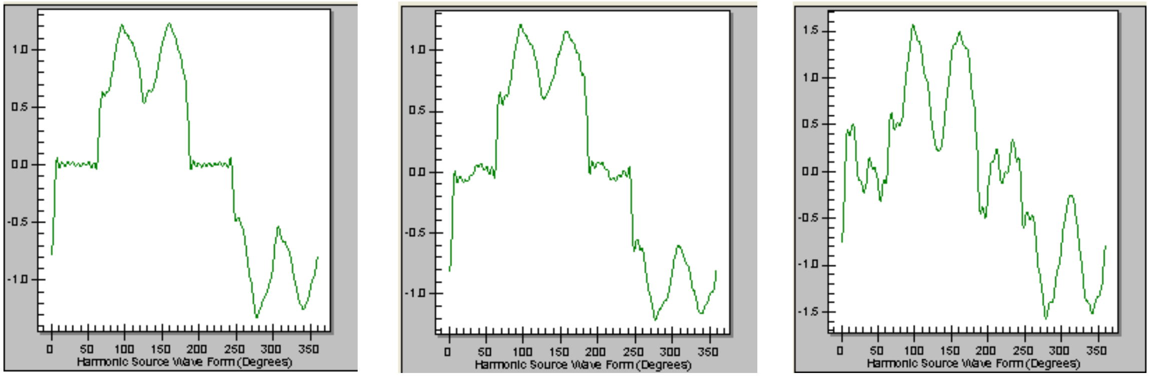


Fig. 2 Model Representation of Loads

Fig. 3 illustrates harmonic signatures used for three drives.



a) b) c)

Fig. 3 Harmonic Signatures

In an ideal case of two 6-pulse halves connected through a phase shifting transformer, there should be no 5th and 7th harmonics on the primary side of that transformer due to the cancellation effect of the 30-degree phase shift. Although the system consists primarily of 12-pulse drives, the harmonic readings show significant values of 5th and 7th harmonics in parts of the system. The cause is incomplete phase shifting, either due to imbalances in individual 6-pulse harmonic output of each side of a drive, or imperfections in the transformer. The existence of 5th and 7th harmonics is added to the model by adjusting a number of the phase shifting transformers phase angles from the ideal 30-degrees.

In general, the worst-case harmonic analysis results are realized when all harmonic current loads are co-phasal (harmonic loads are all in phase), which cannot be achieved in practice. This is done in the model by changing the phase angles of harmonic loads.

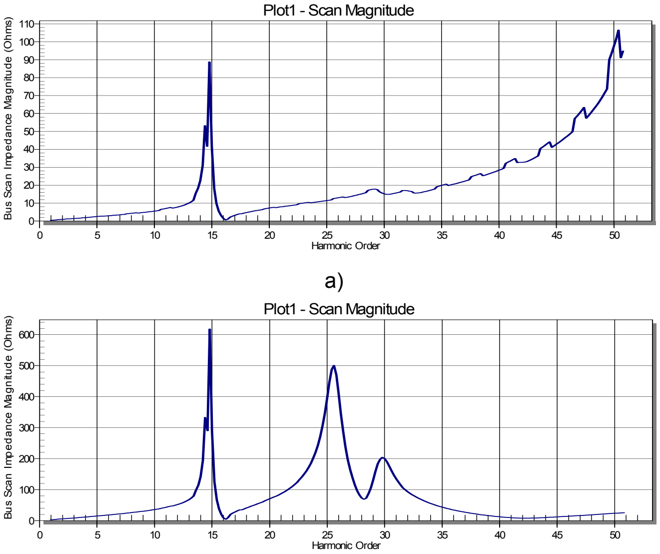
The model assumes normal generation levels of 58 MW and 40 MVAR. It should be noted that the size of the harmonic filters, i.e., amount of capacitive VARS is limited by the need to generate sufficient inductive VARS (volt-amp reactive) to maintain generation system stability.

Why did the initial harmonic analysis and model not properly represent the field measurement conditions? The first clue was the disparity between the current and voltage harmonic values. Normally, there is a close proportional relationship between current distortion and voltage distortion. The lack of a proportional relationship pointed to a possible resonance condition between the system inductance and capacitance.

Two elements are required to create a resonant condition: 1) an excitation source of harmonic current, and 2) an electric circuit with a natural frequency that matches or nearly matches the excitation source frequency. With full or even partial resonance, voltage distortion can multiply many times the “normal” system impedance generated harmonic voltage.

For resonance to occur, the system must have a substantial percentage of capacitance. Where did the capacitance originate without actual capacitors in the system? Upon closer examination of the system, it became clear that a more accurate model of the insulated cables was necessary. This was not a straightforward task, as there are over 125 km of overhead 69 kV lines and an extensive network of 50 km of insulated13.8 kV cable with lengths ranging between 50–500 meters. Surge capacitors used for transient protection on the large rotating machines (generators and motors) were another capacitive element.

Once the model correctly represented the actual field conditions, the harmonic analysis generated the following typical example figures. Bus scan impedance (Fig. 4), voltage waveforms (Fig. 5) and harmonic magnitude spectrums (Fig. 6) are shown for one generator bus and one 13.8 kV substation bus.

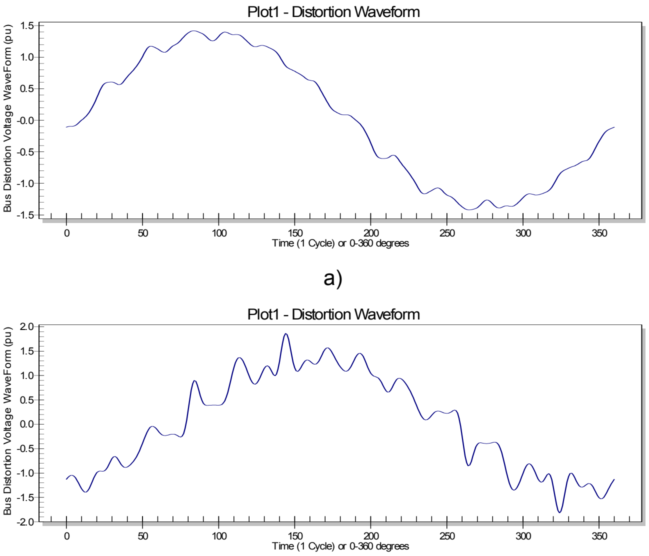


a)

b)

Fig. 4 Scan Impedance
a) Generator Bus b) Substation 13.8 kV bus

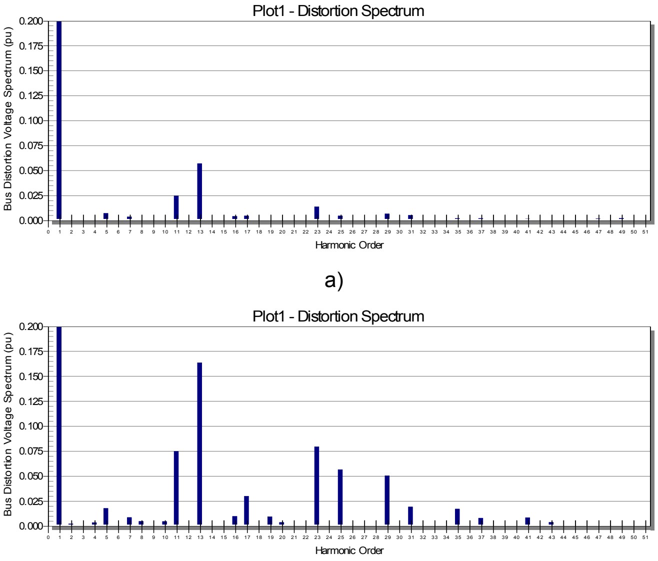
In general, parallel resonance in a system is present at a frequency where impedance has very high value. From the above figures, it can be seen that there are several frequencies where resonance occurs in the system: the first two are at 11th and 13th harmonics, then at multiples of these harmonics (23rd and 25th). There is also some resonance at the higher 30th harmonic frequency. The first harmonics are expected in a system that consists of 12-pulse drives. The higher order peaks are a direct consequence of the characteristics of cables and transmission lines and their capacitance.



a)

b)

Fig. 5 Voltage Waveforms
a) Generator bus b) Substation 13.8 kV bus



a)

b)

Fig. 6 Harmonic Magnitude Spectrum
a) Generator bus and b) Substation 13.8 kV bus

Fig. 5 shows the voltage waveforms for the same buses. High levels of distortion of the sinusoidal waveform can be seen. The sinusoidal wave is profoundly distorted closer to the harmonic loads, in this case the substation 13.8 kV bus. Added to the resonance generated voltage distortion, is the system impedance generated voltage distortion. Due to the voltage divider effect of these impedances, voltage distortion increases nearer to the source of harmonic current and is at a maximum at the input to the ASD.

Fig. 6 shows the harmonic magnitude spectrum for the same buses. Individual harmonic levels are far above acceptable levels. Predominant individual harmonics are 5th, 11th and 13th, and their multiples at the 23rd and 25th, as well as some higher harmonics.

TABLE 1 provides a summary of the measurements. For each substation bus, one feeder was used as a representative measurement.

TABLE 1:
SUMMARY OF HARMONIC READINGS

	VTHD (%)	**ITHD (%)**
Generators		
DG02	4.30	2.50
DG15	5.30	4.00
DG19	7.50	4.80
ST02	6.80	3.70
HV Lines		
A	3.20	10.70
B	2.20	5.90
C	5.70	4.10
D	6.20	3.80
Substations		
T-1 F2	14.90	8.20
T-2 F7	14.90	15.50
C-1 F3	10.80	20.00
C-2 F7	13.60	17.70
H-1 F1	12.90	7.40
H-2 F8	9.70	6.90
S F1	13.10	10.50
Q	10.30	27.10
H	10.70	4.90

TABLE 1 shows that the generators' terminals are exposed to a high level of voltage distortion. Other key points shown in the measured data are as follows:

Significant voltage distortion at the 11th and 13th is present at virtually every bus. It should also be noted that the 13th is larger than the 11th with a few exceptions:

- 13.8 kV load buses: 11th ranges from 3.8 to 9.8% and 13th ranges from 5.5 to 14.2%
- Generator buses: 11th ranges from 2.6 to 4.1% and 13th ranges from 2.7 to 6.1%
- High line measurements: 11th ranges from 1.6 to 2.2% and 13th ranges from 2.1 to 5.6%
- Voltage distortion at the 5th is also present: about 1% on highline, less than 1% at generator buses. In the field, this harmonic ranges from 0.8% to 4.0%

Field Substation Resonances:

- C 1: 1-2.5%, 15-35th
- C 2: 1-4%, 15-29th
- T 1: 1-6%, 15-25th and 3-5%, 47-49th
- T 2: 1-5%, 23-37th with a focus at 31
- H 1-4.5%, 29-49th
- He 1: 1-3.5%, 23-41
- He2: 1-1.5%, 15-25th and 35-49th
- Q: 1-2.5%, 35-49th
- S: 2-3.8%, 17-35th

VII. SOLUTION

After a detailed analysis of the system, with many possible configurations examined, the most appropriate solution was selected. Due to the large size of the power system and the extensive filtering necessary, special consideration was devoted to optimizing the effects using the fewest filters possible and choosing filter locations that provide the best results.

The most effective, robust, and economical harmonic mitigation solution chosen for this system is to install five 13.8 kV multi-element harmonic filters distributed at major substation in the field and one multi-element filter at the 69 kV bus near the generators.

In general, for maximum filter effectiveness, the filters should be located close to harmonic loads. The number of drives in the system and the geographic dispersion of these loads required a different approach for economic reasons and to avoid complexity in the design.

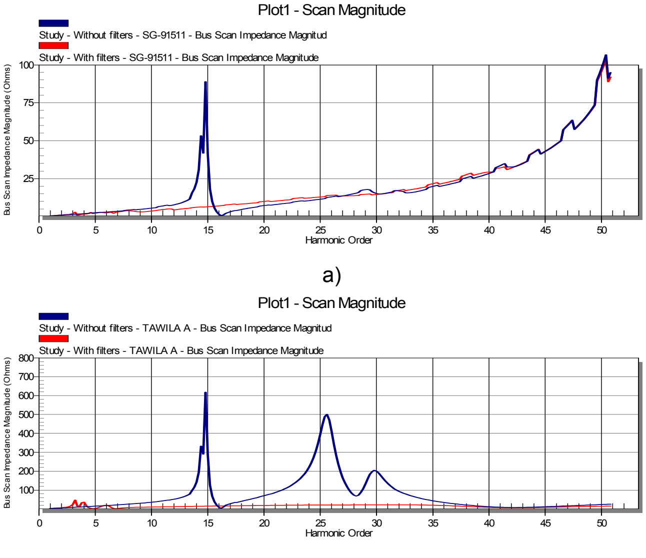
Connection to the main 69 kV substation and five 13.8 kV field substations closer to the loads is an effective compromise. This design will result in levels within IEEE limits at the 13.8 kV buses and at the higher voltage transmission voltage level. At the well site loads, voltage distortion levels will be substantially reduced from 15-30% to 1-8%. Ideally, we would like to see voltage distortion below 5% throughout the system; however, in consultation with the owner, it was decided that this design was a considerable and effective improvement and an acceptable tradeoff between cost and performance.

From the frequency scan results shown in Fig. 9, it appears that the first two resonant points are at the 11th and 13th harmonic. Effectively the system has only 12-pulse drives and these drives will mainly contribute 11th and 13th harmonics into the system. This coincides with measured and modeled data. At first glance, it appears that the filters can be easily tuned to eliminate only the problematic resonance frequencies. This approach is not recommended as it ignores the resonance effects of the filter tuning on the lower order 5th & 7th harmonic characteristic frequencies. In effect, the filter appears as a capacitive element to the system at these lower frequencies. It would introduce a new resonance point at lower frequencies and could be excited by lower order harmonic currents. The solution requires addressing both the characteristic 5th and 7th harmonics and well as the higher 11th and higher frequencies to effectively treat the system and filter any residual currents at the lower frequencies.

Since the main goal of filter selection is to remove specific harmonic currents, filter tuning frequency is selected based on this criteria. Numerous simulations were performed on the examined system in order to get the best technical and economical results. The recommended solution consists of:

- One (1) four-element harmonic filter (stages are tuned for 5th, 7th, 11th and 13th harmonic) together with one high pass filter connected at the 69 kV bus. Each of the 69 kV 5th, 11th and 13th harmonic elements is rated 2400 kVAR, 7th harmonic filter is rated 1200 kVAR, while high pass filter is rated 3000 kVAR.
- Five (5) two-element harmonic filters (tuned for 5th and 7th harmonic) with one high pass filter connected at five substation buses. Each filter is rated for 13.8 kV and 5th filter bank is rated 1200 kVAR, 7th filter bank is rated 600 kVAR, while high pass filter is rated 1200 kVAR. These filters were designed to be identical, for ease of installation and maintenance.

The proposed design option will bring significant improvement in harmonics' cancellation. In the following figures, scan impedance (Fig. 7), voltage waveforms (Fig. 8) and harmonic magnitude spectrums (Fig. 9) are shown for the same chosen buses (in red) as above and compared with the system without filters (in blue).

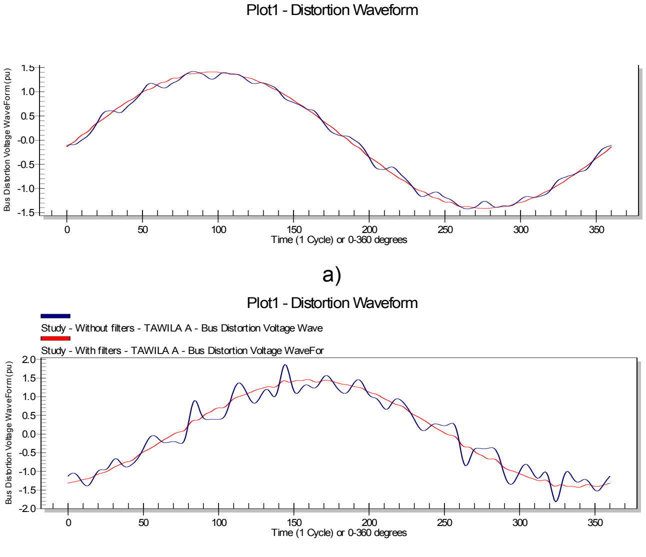


a)

b)

Fig. 7 Scan Impedance: without (blue line) and with filters (red line) *a) Generator bus and b) Substation 13.8 kV bus*

Fig. 7 demonstrates that superior damping of the existing resonance can be expected with the installation of harmonic filters.

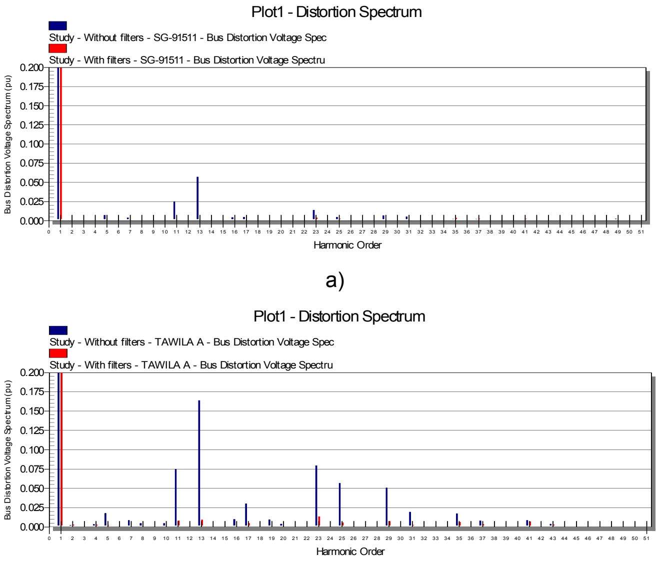


a)

b)

Fig. 8 Voltage Waveforms: without (blue line) and with filters (red line) *a) Generator bus and b) Substation 13.8 kV bus*

Fig. 8 shows major improvement of voltage waveforms that can be expected.



a)

c)

Fig. 9 Harmonic Magnitude Spectrum: without (blue line) and with filters (red line)
a) Generator bus and b) Substation 13.8 kV bus

Fig. 9 demonstrates the mitigation effect of installed filters on the voltage harmonic spectrum and the cancellation or significant damping effect on all harmonics.

The presented solution for harmonics mitigation has the following advantages:

- Cancellation of 5th, 7th, 11th and 13th harmonics at almost every bus, especially at generators' terminals. The values of 11th and 13th harmonics on the worst case 13.8 kV bus without filters connected are below 1.5% and are within the prescribed IEEE Standard 519 limits. The 11th and 13th are eliminated on the generators' terminals.
- Higher order harmonics and resonances (17th and up) are dealt with by the high pass element, regardless of the actual point of resonance.
- Voltage distortion levels are reduced in the entire system. Voltage total harmonic distortion levels will be below the maximum of 5% recommended by IEEE 519.
- The system utilizes the same filter configuration at all the required 13.8 kV substations.

VIII. CONCLUSIONS

The harmonic filter design presented in this report is an effective, robust and economical solution to the harmonic problems affecting the operation, reliability and maintainability of the studied power system.

Designing harmonic filters for large systems is not trivial and can be highly challenging. Using real world data to verify the validity of computer models becomes increasingly critical as the system grows in size, complexity and age—when equipment is more likely to operate unlike idealized models.

Harmonic analysis was conducted and harmonic indices developed for a large isolated power system supplied by on-site generators. Fig. 1 shows a single line diagram of the system, labeled with before and after harmonic levels in the system.

The recommended filter solution significantly reduces harmonic distortion. All 13.8 kV filters are matching designs to make maintenance and parts replacement simple. Provided engineering checks are completed, it presents a modular approach for future expandability using similar designs, and the ability to maintain comparable performance at even higher loads.

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