



OTC 17095

Harmonics in Offshore Electrical Power System

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This paper was prepared for presentation at the 2005 Offshore Technology Conference held in Houston, TX, U.S.A., 2-5 May 2005.

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Abstract

Recently Electrical Submersible Pumps (ESPs) are being widely used in the depleting oil fields with low pressure (Dead Crude) and in deep wells with marginal pressure to achieve oil production. These ESPs are variable speed drives (VSDs) and operated at variable voltages and frequencies to optimize production. The introduction of large amount of ESP driven by VSDs into an electrical power system of an Offshore Oil Field, which is electrically weak, leads to distortion of voltage and current profile beyond acceptable limits, thereby producing harmonics. More the distortion in waveform higher are the harmonics.

The concept of harmonics along with their impact and mitigation measures to be exercised in an Offshore Power System has been discussed in this paper. Further, a method statement is provided for sizing the Active Harmonic Filter (AHF). An attempt is made to arrive at empirical relationship for AHF rating in kVAR for Offshore Electrical Power System, which is not yet well documented. A case study of harmonic analysis for an integrated offshore field in South China Sea has been discussed.

It is concluded that AHF is the optimum choice for an Offshore Power System in view of its flexibility, better harmonic control, reliability, power factor improvement and least space requirement.

The information contained in this paper shall be useful for design engineers as well as operators handling Electrical Power System for Offshore Oil Field with significant amount of non linear loads or variable speed drive loads. This shall enable them to predict the requirement of harmonic treatment in Offshore Electrical Power System. It will also help them to take early action at planning / design stage to avoid probable damage to equipment or loss of power due to harmonics and to conduct detailed harmonic analysis.

Introduction

Highly reliable and high quality power supply is of paramount importance in Offshore Oil and Gas installations. Power outage and poor power quality cost heavily in these installations. Power quality is defined in terms of voltage variation, voltage transients and voltage waveform. One of the power quality characteristics lies in its waveform. It is preferred to have power supply waveform as close as possible to that of a pure sine wave. In reality the power supply waveform is never pure sinusoidal. The power supply waveform gets distorted due to non linear loads, rectifiers, variable speed drives, arc furnaces, fluorescent tubes, discharge lamps, fan regulators, and other power distribution equipment. The waveform distortion is identified as combination of fundamental sinusoidal waveform and harmonics.

Harmonics are pollution and impact quality of power and life of electrical equipment. They need to be contained and can be contained by adopting mitigation measures as discussed in this paper. It has long been recognized that harmonic currents and voltages are highly detrimental to electrical power equipment and system. Their presence can damage equipment and disrupt production process thereby costing heavily to the Offshore Oil and Gas operators.

Concept of Harmonics

The harmonics are defined as sinusoidal components of a periodic wave having a frequency that is an integral multiple of fundamental frequency. This concept was developed by Fourier. As per Fourier theorem any periodic function with frequency 'f' may be expressed as a sum of the following terms.

- A sinusoidal term with frequency ' f_0 ' being the fundamental component and termed as fundamental frequency.
- A series of sinusoidal terms with frequencies that are whole multiple of the fundamental frequency. i.e. harmonics.
- A DC component, if applicable.

The application of Fourier series to voltage and current of non linear loads help to understand the non linear and non sinusoidal behavior of voltage and current in power system. The periodic current or voltage of this type (whatever form) at frequency 'f' is the sum of fundamental and harmonic sinusoidal currents/ voltages defined by:

$$I_t = I_1 \sqrt{2} \sin(\omega t + \theta_1) + \sum I_{hn} \sqrt{2} \sin(n\omega t + \theta_n)$$

$$V_t = V_1 \sqrt{2} \sin(\omega t + \theta_1) + \sum V_{hn} \sqrt{2} \sin(n\omega t + \theta_n)$$

Where

I_t = Total current

V_t = Total Voltage

I_1 = RMS value of fundamental current

V_1 = RMS value of fundamental Voltage

I_{hn} = RMS value of nth harmonic current at frequency nf

V_{hn} = RMS value of nth harmonic voltage at frequency nf

$\omega = 2\pi f$

$n = 2, 3, 4$ (Natural Numbers)

θ_1 = Phase displacement between fundamental current and voltage.

θ_n = Phase displacement between the nth harmonic current and voltage.

The behaviour of non sinusoidal currents and voltages in the Power system can be predicted with the help of harmonics. The harmonics are the mathematical tools which help in analyzing and predicting the voltage and current profile in the network.

Figure-1 below shows how the wave form gets distorted with the presence of harmonics.

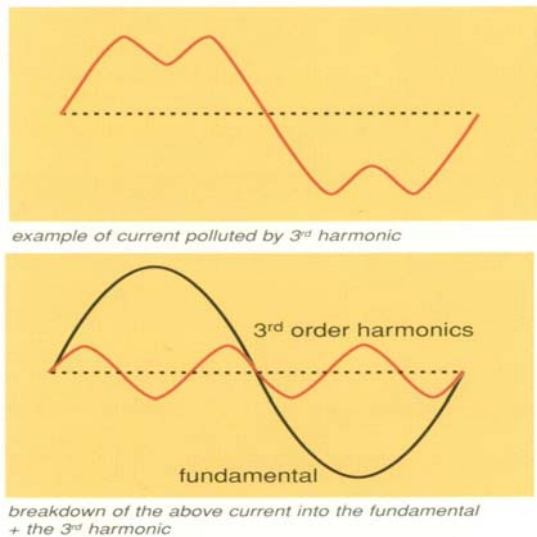


**FIG-1
HARMONIC COMPONENTS**

In Electrical power system current and voltage harmonics do exist with frequencies that are integral multiples of the fundamental power frequency, e.g. for 50 Hz fundamental frequency the 2nd harmonic is 100 Hz and 3rd harmonic is 150 Hz and the 5th harmonic is 250 Hz. Each harmonic is also expressed as a percentage of fundamental.

$$I_{Hn} = 100X \frac{I_{hn}}{I_1}$$

Where

I_{Hn} = Percentage value of nth Current harmonic

$$V_{Hn} = 100X \frac{V_{hn}}{V_1}$$

Where

V_{Hn} = Percentage value of nth voltage harmonic

The total RMS current and voltages are expressed as

$$I_{rms} = \sqrt{I_1^2 + I_{h2}^2 + I_{h3}^2 + \dots + I_{hn}^2}$$

$$V_{rms} = \sqrt{V_1^2 + V_{h2}^2 + V_{h3}^2 + \dots + V_{hn}^2}$$

The total harmonic distortion for current THDI and for voltage THDV is expressed in percentage as

$$THDI = 100X \frac{\sqrt{I_{h2}^2 + I_{h3}^2 + I_{h4}^2 + \dots + I_{hn}^2}}{I_1}$$

$$THDV = 100X \frac{\sqrt{V_{h2}^2 + V_{h3}^2 + V_{h4}^2 + \dots + V_{hn}^2}}{V_1}$$

Note: The total harmonic distortion some times is expressed with respect to contractual demand current I_L and not the fundamental. This is then termed as total demand distortion.

Harmonic Producing loads

The increasing use of computer, telecommunication equipment and power electronic devices such as electrical submersible pumps (ESPs), variable speed drives, DC drives for drilling, programmable logic controllers (PLCs), trans-receivers, amplifiers, fluorescent tubes, air conditioners, discharge lamps, uninterrupt power supply (UPS) systems, battery chargers etc on offshore installation contribute harmonics in power system. A load that draws non sinusoidal current when supplied from sinusoidal voltage source leads to harmonic current generation. A non sinusoidal current when passes through a linear impedance results in non sinusoidal voltage. The non sinusoidal voltage leads to distortion of system voltage waveform identified as voltage harmonics.

Non linear loads, such as converters / rectifiers and inverters draw currents in abrupt pulses rather than in smooth sinusoidal manner. These pulses of current passing through system impedance result in voltage distortion which in turn leads to harmonic currents in other equipment. Single line in Fig-2 below shows how a converter current harmonics (i_h) in the load current (i_s) leads to supply voltage (u) distortion and injection into other electrical loads.

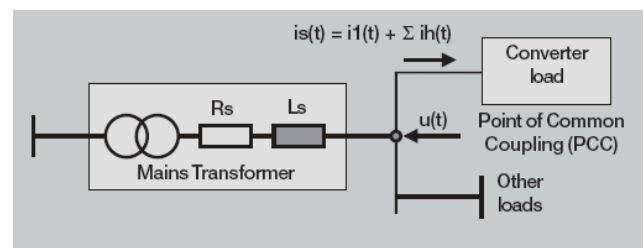


**FIG-2
HARMONIC CURRENT PRODUCTION**

Typical harmonic current generated in a converter / rectifier can be calculated using simple mathematical formula. The steps followed for calculating the harmonic currents in six pulse rectifier are described below.

STEP-1

The line current (I_{rms}) of a three phase six pulse rectifier can be calculated from the output DC current (I_d) by using the formula:

$$I_{rms} = \sqrt{2/3} \times I_d$$

STEP-2

The fundamental current I_1 is then

$$I_1 = \frac{3I_{rms}}{\pi}$$

STEP-3

Where output DC current I_d can be estimated as clean DC, and there is no ripple content, the harmonic currents and their frequencies can be calculated as follows:

$N = 6k \pm 1$, where k is integer $k = 1, 2, 3, \dots$

The harmonic current I_h

$$I_h = I_1 / N$$

The harmonic frequency f_h

$$f_h = N f_0$$

Considering fundamental current as 100 % the 5th, 7th, 11th, 13th, 17th and 19th harmonic current content is shown below in Figure-3 for 6 pulse rectifier.

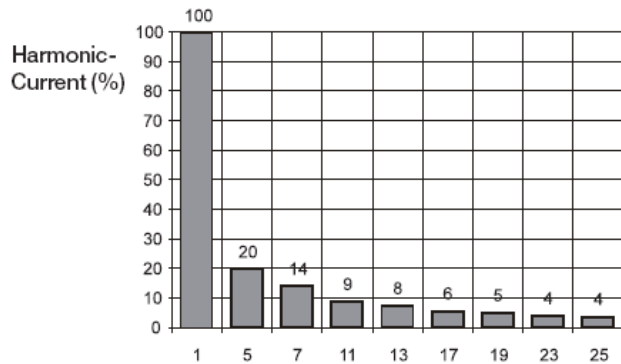


FIG-3
HARMONIC CONTENT

The typical harmonic current contributed by industrial rectifiers as indicated above are theoretical values but in reality these values are even higher.

Synchronous generators also do produce 5th harmonic voltage due to magnetic flux distortion near stator slots and non-sinusoidal flux distribution across air gap. Further iron core devices such as transformers, reactors and motors draw nonlinear magnetising current at magnetic saturation. The non linear magnetic characteristic of iron core is described by a hysteresis curve. This also leads to voltage waveform distortion.

Effect of Harmonics

The increased presence of harmonics is a relatively new phenomenon that concerns all Offshore Oil & Gas electrical installations. No modern electrical power system is exempt

from the disturbances due to increased use of power electronic devices. The impact of harmonics can be classified in three categories:

Increase in current

Increase in losses

Disturbance in operation of sensitive equipment

Harmonics increase the magnitude of rms current with respect to that of rated sinusoidal current. The result is over loading of power cables, bus bars, transformers, capacitors, generators, motors etc.

Harmonics lead to an outright loss of useful power. User has to pay more for less available power in addition to transmission power losses due to increased current.

The distortion in supply voltage disturbs the operation of sensitive equipment. The circulating harmonic current leads to electromagnetic interference with other communication equipment.

Presence of harmonics can lead to:

Current distortion

Voltage distortion

Increased system losses and overheating

Shorten the life of power system equipment

Mal-operation of sensitive electronic equipment

Interference with telecommunication equipment

Effect on other consumer equipment fed from the same system

Error in metering

Neutral circulating currents

Capacitor bank overloading and failures

Over voltage / over current due to harmonic resonance

High neutral ground voltage

Transformer over heating

Induction motor overheating

Pulsating torque in induction motors

Malfunction of protective relays

Generator voltage instability

Effects on Power Equipment

All power equipment are affected by harmonics. Transformers, cables, bus bars, bus ducts, switchgears etc are overheated due to flow of harmonic currents. Induction motors get overloaded and produce pulsating torque which can damage the driven equipment. Harmonics increase copper losses, eddy currents and hysteresis losses in generators, transformers and motors. Harmonics increase stress on insulation due to voltage distortion and impact the life of equipment. Lighting equipment may get damaged or start to flicker. The 5th Harmonic voltage (negative sequence) distortion leads to increased losses in induction motors. High frequency harmonics will incur increased losses due to skin effects. Generally, performance of all electrical equipment is affected due to voltage distortion. The Vacuum and SF6 circuit breaker technologies are based on zero crossing. It is difficult to quench the harmonic currents with these breakers. Presence of harmonics can lead to pitting of contacts during switching.

Effects on Capacitor Bank

Capacitor banks are the worst affected equipment by harmonics. Capacitor impedance decreases with increase in frequency i.e. capacitor bank acts as a sink to all harmonics. It amplifies the harmonic currents due to low impedance. Apart from its rated current, the capacitor will carry amplified harmonic currents which may overload the capacitor bank and ultimately lead to failure of the capacitor. Any L-C resonance due to harmonic presence will magnify the problem of over voltage and / or over current.

Effects on Electronic Equipment

The voltage waveform distortion causes malfunction of electronic equipment. Transducers, relays, computers, panel view etc operate on narrow voltage window. Voltage distortion beyond acceptable limit impacts their performance and life. Analogue controllers, sensors, switching devices are adversely affected by voltage distortion. This is especially so when timing circuits use zero crossing point as reference. Presence of neutral ground voltage impacts the reference voltage and affects the set point controls. The presence of harmonics creates interference with communication equipment. The power line carrier communication circuits are affected by harmonics in the main power system.

Effects on Neutral Currents

All third harmonic currents will add up to neutral current. Neutral currents further increase with unbalanced single phase loads. High neutral current increases neutral ground voltage which adversely affects communication equipment or system controller. Neutral conductor size (normal ½ size) may get over loaded and over heated

Generally circuit breakers are not provided in neutral for overload protection. If available it may trip service due to third harmonic / triplen current

Generator windings are not designed to take continuous neutral currents. High neutral currents may damage generator. Core Balance Current Transformer (CBCT) based sensitive earth fault protection will mal-operate if third harmonic currents are present in the system.

Harmonic Resonance

In an L-C circuit, resonance occurs at a frequency at which inductive impedance equals capacitive impedance ie $X_L = X_C$

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

Where:

f_r - is resonance frequency

L- is inductance of the circuit

C- is capacitance of the circuit

$$f_r = \frac{1}{2\pi} \sqrt{\frac{1}{LC}}$$

If resonance frequency f_r is close to harmonic frequency f_h , then harmonic frequency currents will be amplified by resonance. Under series harmonic resonance, high currents

will flow and damage the equipment due to over current. Under parallel harmonic resonance high voltage will establish across capacitor bank and damage the equipment due to over voltage. If resonance frequency is less than power system frequency ($f_r < f_0$), it may be amplified by synchronous generators in the system.

Why Control Harmonics?

As already explained harmonics cause pollution, impact quality of power and act as parasites in the Power System. Harmonics cause damage to equipment and disruption to production process, can cause overheating, produce electromagnetic interference to other control / communication equipment. Harmonics produced by one industrial user may impact the equipment of other user on the same power system. Presence of harmonics can lead to wrong metering of power at consumer premise and nuisance tripping of power supply.

Even harmonics ie 2nd, 4th, 6th etc are negative sequence and generate pulsating torque in motors and generators.

All these problems, losses and side effects of harmonics necessitate steps to be taken to mitigate harmonics in power system.

Harmonic Analysis

The purpose of harmonic analysis is to arrive at the total harmonic distortion at various locations in power system. Generally following Computer based harmonic analysis are carried out:

Harmonic analysis for current harmonics

Harmonic analysis for voltage harmonics

The computation of total harmonic distortion resulting from harmonic producing loads requires knowledge of non linear load characteristics and system frequency response characteristics. Most non linear or harmonic producing loads are simulated as ideal current source for analysis purpose. The order and strength of each harmonic as percentage of full load is obtained from manufacturer. The non linear load characteristics are determined by signature analysis and harmonic spectrum of the equipment. This information is used for system harmonic analysis.

Once the harmonic producing load characteristics are determined, the response of the system to these loads is calculated by commercially available electrical system analysis softwares such as EDSA / ETAP etc. The voltage and current profiles for each harmonic frequency is determined by Newton-Raphson iterative method and vectorial summation is obtained to arrive at the net impact on the network voltage and currents.

Measurement of Harmonics

The measurement of current and voltage harmonics is essential for determining the mitigation approach. The techniques used for harmonics measurement are different from those used for ordinary power system parameters. This is due to the higher frequencies involved. Following devices and

instruments are used for measurement and analysis of harmonics.

Oscilloscope The display of waveform on the oscilloscope gives immediate qualitative information on the degree and type of distortion.

Spectrum Analyzers These instruments display the signal strength for scanned frequency. A certain range of frequency is scanned, and all the components are analyzed.

Harmonic Analyzers These instruments measure the amplitude of a periodic function and provide the line spectrum of an observed signal.

Distortion Analyzers These instruments measure the Total Harmonic Distortion (THD) voltage (THDV) or current (THDI) directly at any point in the Power System.

Harmonic standards

Harmonic distortion limits (voltage and Current) are defined in following standards:

- 1.0 IEEE 519
- 2.0 IEC 61000
- 3.0 Engineering Recommendation G. 5/3 (UK Electricity Council Engineering Recommendation)

Generally standards specify limits to total harmonic distortion and individual harmonic limits for both voltage and current. The individual harmonic currents and Total Harmonic Current Demand Distortion (TDDI) limits as defined in IEEE519 as percentage of maximum demand load current (I_L) are indicated below in table-1 for industrial system

Table-1
CURRENT DISTORTION LIMITS

Vn<69 kV						
I_{sc}/I_L	h<11	11<h<17	17<h<23	23<h<35	35<h<	TDDI
<20	4	2	1.5	.6	.3	5%
20~50	7	3	2.5	1	.5	8%
50~100	10	4.5	4	1.5	.7	12%
100~1000	12	5.5	5	2	1	15%
>1000	15	7	6	2.5	1.4	20%

IEEE 519 does not define voltage distortion limits at distribution level for an Industrial system. It defines voltage distortion limits at Point of Common Coupling (PCC). PCC is the point where power supply company contract power to the consumer. In Offshore Electrical Power System, PCC is not applicable. However the maximum Total Harmonic Voltage Distortion (THDV) at PCC is defined as 3% for special application, 5% for general system and 10% for dedicated system. These voltage distortion limits can be considered for Offshore Electrical Power System.

The individual harmonic voltage and total harmonic voltage distortion limits as defined in IEC 61000 as percentage of

fundamental voltage are indicated below in table-2 for industrial system. These values can be applied to Offshore Electrical Power System.

Table-2
VOLTAGE DISTORTION LIMITS

Harmonic Order	Class-1 Sensitive equipment	Class-2 Industrial Network	Class-3 Big Polluters
2	2	2	3
3	3	5	6
4	1	1	1.5
5	3	6	8
6	.5	.5	1
7	3	5	7
8	.5	.5	1
9	1.5	1.5	2.5
10	.5	.5	1
11	3	3.5	5
THDV	5%	8%	10%

For most of the Offshore Electrical Power Distribution System, maximum total harmonic voltage distortion of 5% ~ 8% and maximum total current distortion 5% ~12% is recommended.

Mitigation Measures

Given below are some of the harmonic control techniques used in the industry to mitigate impact of harmonics in Electrical Power System.

Control at harmonic source

Neutral Isolation

Isolation transformer

Line reactors

Phase Multiplication

De-rating of equipment

Passive filters

Active filters

Isolated Gate Bipolar Transistor

Regrouping of the Polluting loads

Controls at Harmonic Source

Harmonic control at the source (Harmonic producing Load) is the best option to control harmonics. All possible techniques such as line reactors, passive filter, isolation transformer neutral isolation etc are applied in the device to control harmonics. However these techniques in some cases either become uneconomical or unfeasible due to size or number of components.

Neutral Isolation

In three phase power system, the third harmonic and multiple of third harmonic (triplen) add to neutral currents. If neutrals are isolated to the harmonic producing loads, third harmonic current and its multiple i.e. 6th, 9th, 12th etc shall get eliminated automatically. This technique is normally used for all harmonic producing loads.

Isolation Transformer

Isolation transformers are used to provide electrical isolation between distribution system and harmonic producing load. Isolation transformers are used for neutral isolation; phase shifting and dual supply for 12-Pulse converter. Isolation transformer often has single or multiple electrostatic shields to reduce common mode noise. They have the ability to change the voltage levels between load and supply, thereby mitigate the harmonic current.

Line Reactor

Line reactor acts as a current limiting device to limit current harmonics and attenuate electrical noises. Normally the line reactors are inserted where isolating transformers are not used between inverter and supply line. Line reactors also help to prevent tripping of drives due to capacitor switching that causes over voltage at DC link of the inverter. It is recommended to use at least 3% impedance line reactor for mitigating harmonic currents as shown in fig-4.

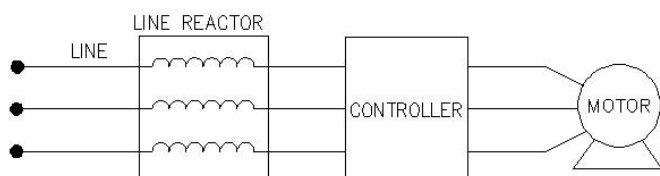


FIG -4
LINE REACTOR

Phase Multiplication

Single phase converters are commonly used for small loads for lowest initial cost, but they produce very high harmonics. Half wave rectifier produces even harmonics that tend to saturate the transformer and therefore, should be avoided and a full wave rectifier should be used instead. Poly phase converters produce different harmonic levels. The most common poly phase converter circuit in three phase AC drive is a 6 pulse rectifier. The 12 pulse rectifier is formed by connecting two 6pulse rectifiers in parallel with 30° phase shift in transformer secondaries. The 24 pulse rectifier has two 12 pulse rectifiers in parallel with two three winding transformers having 15° phase shift. Fig-5 below shows connection for poly phase rectifiers and their relative harmonic content.

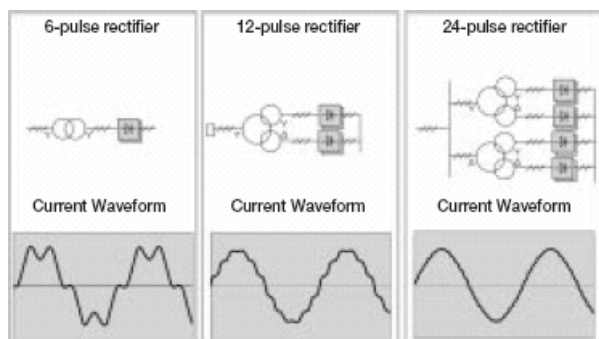


FIG-5
HARMONICS IN LINE CURRENT WITH POLY PHASE RECTIFIERS

It can be easily observed that as the number of pulse increases in the rectifier, the harmonic content (in line) reduces

significantly. Thus higher the pulse better it is for harmonic control. Further rectifier technology has improved and with the use of Isolated Gate Bipolar Transistor (IGBT), the harmonic content in line can be reduced drastically. The relative harmonic content as percentage of fundamental load is shown below in table 3 for 6, 12 and 24 pulses rectifiers along with IGBT rectifier for comparison purpose.

TABLE-3
TYPICAL HARMONIC CURRENT

6 PULSE RECTIFIER WITHOUT INDUCTOR						
I ₁ (Fund)	5 th	7 th	11 th	13 th	17 th	19 th
100%	63%	54%	10%	6.1%	6.7%	4.8%
6 PULSE RECTIFIER WITH INDUCTOR						
I ₁ (Fund)	5 th	7 th	11 th	13 th	17 th	19 th
100%	30%	12%	8.9%	5.6%	4.4%	4.1%
12 PULSE RECTIFIER WITH DOUBLE WOUND TRANSFORMER						
I ₁ (Fund)	5 th	7 th	11 th	13 th	17 th	19 th
100%	3.6%	2.6%	7.5%	5.2%	1.2%	1.3%
ACTIVE IGBT RECTIFIER						
I ₁ (Fund)	5 th	7 th	11 th	13 th	17 th	19 th
100%	2.6%	3.4%	3.0%	0.1%	2.1%	2.2%

Derating of Equipment

Electrical power equipment such as cables, switchgear, bus ducts, capacitor banks, motors, heaters, transformers need to be de-rated based on the harmonic loading and system analysis. Normally, the de-rating shall be based on the total harmonic current distortion (THDi). It is advised to conduct harmonic analysis to identify the harmonic content in the Power Distribution Network and de-rate the equipment accordingly.

Conventional three phase power transformers are not designed to handle third harmonic or triplen. Special designs are to be used in power system having triplens. The triplen harmonics produce response very different from other harmonics. Triplen harmonics circulate in delta winding of a three phase transformer, flow through neutral conductor and impact magnetic circuit. They need to be investigated properly. The triplens induce zero sequence flux, which can over heat tank and damage the core. These transformers must be de-rated by applying a coefficient 'K' to their rated power for harmonic loading. The derating factor is defined in French National standard NFC 52-114 and is calculated as below:

$$K = \frac{1}{\sqrt{1 + 0.1 \sum_{n=2}^{n=\alpha} I_{Hn}^2 n^{1.6}}}$$

Where

K = De-rating Coefficient

I_{Hn} = nth harmonic current as percentage of fundamental

n = nth harmonic order

These transformers are called as K rated transformer and are used invariably where triplen harmonics are present.

Passive Filter

Passive filter or shunt filter reduces harmonics by providing low impedance path to shunt away the harmonics from the system. Passive filters are used upstream of non linear load to limit harmonics on supply bus bars. Passive filters are tuned to a particular frequency to be eliminated and sized for defined load. Any addition or alteration of load renders the passive filter useless. Passive filter helps in improving the system power factor. Passive filter increases the risk of resonance with upstream system specially transformer. There are three types of LC filters generally used in the industry.

- 1.0 Non compensated filter
- 2.0 Compensated filter
- 3.0 Non compensated filter with switching contactor.

Multiple passive filters can be employed to filter different frequencies. The operating principle of a passive filter is shown in Fig-6 below.

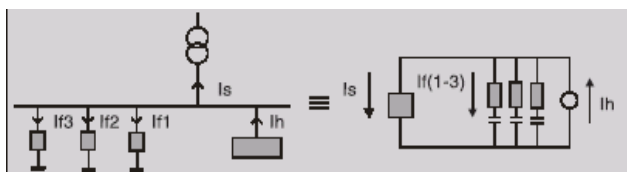


FIG-6
PASSIVE FILTER

Active Filter

An Active Harmonic Filter (AHF) is a power electronic device which produces the harmonic currents required by the load. Active filter work on the principle of real time monitoring of the harmonics and generation of harmonic current required for the compensation. The AHF uses Isolated Gate Bipolar Transistor (IGBT) Bridge to inject the harmonic current on the network in opposite phase of load current of different frequencies. Consequently, the current supplied by the source remains virtually sinusoidal under all operating conditions. The AHF is preferred to be located near harmonic producing load to avoid current circulation. Multiple units can be used to compensate large capacity loads. The operating principle of active filter is shown below in Fig-7.

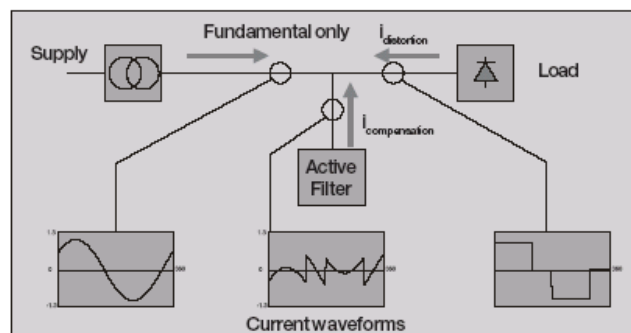


FIG-7
ACTIVE FILTER

The AHF is shunt connected and can be used for power factor correction, current control and phase displacement.

Case Study

Huizhou Oil Field operated by Cnooc, Agip, Chevron and Texaco (CACT) operators group is located in South China Sea approximately 100 miles South East of Hong Kong in water depths ranging from 98 meters to 115 meters. The Offshore field development includes two generation platforms and three wellhead / production platforms. The electrical power generation and distribution system for integrated offshore field comprises of generation at Platform 'A' and 'B' and distribution to platforms C,D,E as depicted in Fig 8. There are four Ruston Gas Turbine Generator sets namely G1, G2, G3 and G4 on Generation platform 'A'. Each rated as 4160V, 5.0 MVA, 0.8 PF to deliver 2800 kW at site conditions. There are three Taurus 60 solar gas turbine generator sets namely G11, G12 and G13 on platform 'B'. Each rated at 4160V, 6625kVA, 0.8PF to deliver 4600 kW at site condition.

Platform 'A' Power Generation is connected to Platform 'C' through a 5 MVA step up transformer via 34.5 kV Submarine Cable. This is referred as link 'A'.

Power Generation at Platform 'B' is connected to Platform 'C' through a 5 MVA step up transformer via 34.5 kV submarine cable. This is referred as link 'B'.

Power Generation at Platform 'B' is also connected to Wellhead cum production platform 'D' through 16 MVA step up transformer to 34.5 kV submarine cable. This is called link 'C'. Wellhead platform 'E' is also connected to Platform 'D' through 34.5 kV submarine Cable and this is referred as link 'D'.

The power generation at Platform 'A' & 'B' are interconnected at Wellhead platform 'C'. The loads of Platform 'C' are fed through step down 10MVA Transformer. The loads of Platform 'D' are fed through step down 12.5 MVA transformer. The loads of Platform 'E' are fed through step down 9.6 MVA Transformer. The Electrical power around 24.0 MW consumed in the field is generated by six Gas Turbine Generators (GTGs) with one standby.

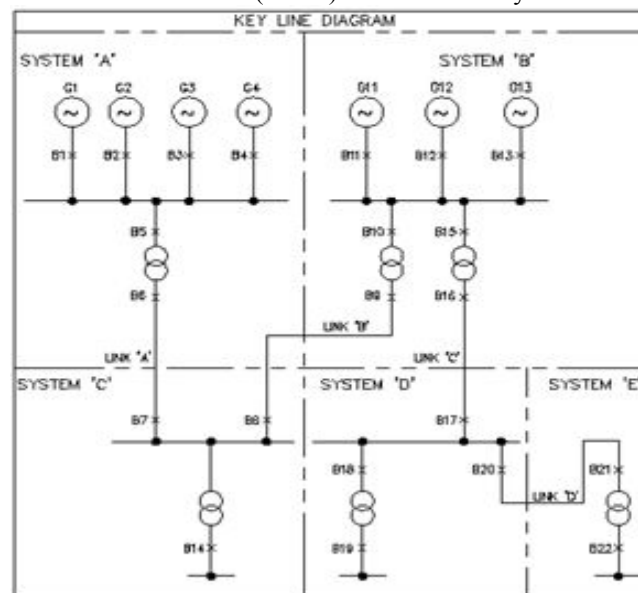


FIG-8
KEY LINE DIAGRAM

Although all the platforms are provided with Electrical submersible pumps (ESPs) for artificial lifting of Oil from the reservoirs and drilling rig for drilling and over hauling but detailed case study is done considering ESPs loads and DC drilling loads at platform 'D' and 'E'. The impact of these non linear loads is evaluated on complete integrated power system. The ESPs load at platform 'D' & 'E' are fed at 480V through dedicated 2500 KVA transformers. The DC loads of drilling rig are fed at 600V through 5000KVA transformer. Total ESPs load on platform 'D' is 1850kW and on platform 'E' is 1350kW. The harmonic content as percentage of full load in each ESP drive and DC drive is as shown in table 4 below:

Table-4
HARMONICS IN ESP AND DC DRIVES

HARMONIC ORDER	ESP DRIVES	DC DRIVES
1	100	100
5	30	23.5
7	9.8	10.0
11	5.7	8.3
13	3.5	5.6
17	2.2	4.6
19	1.7	3.5

In addition to above other non linear loads such as UPS, battery chargers and thyristor controlled heaters are also considered to evaluate the total harmonic distortion in the system. A maximum of two DC drilling motors operating simultaneously have been considered during drilling.

For the purpose of harmonic analysis all six generators at platform 'A' & 'B' are considered running with supporting loads of respective platforms. The drilling rig on platform 'D' and ESP load on platform 'D & E' along with non linear loads have been simulated for harmonic analysis. The harmonic analytical study has been conducted on commercially available software. Total harmonic distortion in terms of voltage and current distortion in the network as well as on platform 'D' are reported below in table-5.

TABLE-5
HARMONIC DISTORTION WITOUT AHF

BUS	I _{THD}	V _{THD}
1(HV-BUS)	3.56%	5.7%
2(MV-BUS)	2.54%	7.28%
3(LV-ESP BUS-01)	26.67%	11.92%
4(LV-ESP BUS-02)	26.45%	11.41%
5(LV-BUS)	5.88%	7.28%
6(LV-BUS)	4.87%	6.53%
7(LV-BUS)	4.69%	6.52%
8(MCC-1)	5.88%	7.28%
9(MCC-2)	5.36%	6.53%
10(MCC-3)	7.31%	6.52%
11(DRILL-BUS-01)	16.06%	11.58%
12(DRILL-BUS-02)	23.97%	11.64%
13(HV-PTF-B)	2.77%	2.17%
14(HV-PTF-A)	0.58%	0.45%
15(HV-PTF-C)	0.88%	1.2%
16(MV-PTF-C)	5.92%	1.24%

From table-5 it can be observed that total voltage distortion at ESP switchboard (LV-ESP-BUS 01/02) and drilling rig switchboard (DRILL-BUS 01/02) exceeds normal industry accepted level of 8% (Refer Table-2). It has resulted voltage distortion from 2% ~8% in the rest of main system. These voltage distortions in Offshore Electrical Power System were found to be beyond acceptable limits.

In order to mitigate harmonic distortion and bring them acceptable levels, various techniques were evaluated. Passive filter at distribution bus was ruled out due to varying loads and large space requirement. The 12 pulse rectifier was a possible solution to ESP bus but not found attractive due to additional transformers and commercial reasons. Finally AHF was considered to be the optimum choice for the system.

By applying 250 KVAR Active Harmonic Filter (AHF) on each bus of ESP switch board, a total of 500kVAR on each platform, the system voltage and current distortion were reduced to acceptable limits as reported below in table-6.

TABLE-6
HARMONIC DISTORTION WITH AHF

BUS	I _{THD}	V _{THD}
1(HV-BUS)	2.24%	3.81%
2(MV-BUS)	2.22%	5.16%
3(LV-ESP BUS-01)	17.67%	7.26%
4(LV-ESP BUS-02)	17.43%	6.9%
5(LV-BUS)	4.16%	5.16%
6(LV-BUS)	3.12%	4.50%
7(LV-BUS)	2.96%	4.49%
8(MCC-1)	4.16%	5.16%
9(MCC-2)	3.69%	4.50%
10(MCC-3)	5.63%	4.49%
11(DRILL-BUS-01)	14.82%	11.08%
12(DRILL-BUS-02)	24.30%	11.14%
13(HV-PTF-B)	1.72%	1.45%
14(HV-PTF-A)	0.35%	0.29%
15(HV-PTF-C)	3.6%	0.81%
16(MV-PTF-C)	0.56%	0.77%

The Harmonic Filter on drilling bus though required was not installed in view of limited operation and phased out with production. The total harmonic distortion levels on drilling bus during drilling operation may still be higher than acceptable limits. This was accepted in view of drilling equipment suitability and limited operation and acceptable impact on rest of the system.

AHF Sizing

At present there is no engineering guidelines or standard available for Active Harmonic Filter sizing. The one possible approach for sizing the AHF is described below for application engineers.

STEP-1

Identify the location where maximum current distortion is observed in the network. It shall normally be close to biggest harmonic producing load or set of harmonic producing loads. This will decide the nominal three phase power system voltage V_{rms} and nominal frequency f_0 for AHF.

STEP-2

Estimate the maximum load current I_L at the AHF location for all the harmonic producing loads to be considered for compensation.

STEP-3

Compute total harmonic current distortion as percentage of fundamental for all harmonic producing loads at the AHF location.

$$THDI_i = \text{SQRT} \sum I_{hi}^2 / I_1, \text{ hi} = 2, 3, 4, \dots, N$$

Where

THDI_i = Total Current harmonic distortion initial.

STEP-4

Compute target total harmonic current distortion acceptable as percentage of fundamental for all harmonic producing loads at the AHF location. It can be sourced from the referenced standards.

$$THDI_f = \text{SQRT} \sum I_{hf}^2 / I_1, \text{ hf} = 2, 3, 4, \dots, N$$

Where

THDI_f = Total acceptable Current harmonic distortion final.

STEP-5

Compute current rating of AHF using following formula:

$$I_{rms} = 1.2 * (THDI_i - THDI_f) * I_L$$

Where

I_L = Full load current of harmonic producing load

Compute kVAR rating of AHF using current I_{rms} as above and system nominal voltage V_{rms} at the point of location of AHF in the Electrical power System with following formula:

$$KVAR = \sqrt{3} I_{rms} V_{rms}$$

The KVAR rating of AHF computed above shall be adequate to contain harmonic distortion within acceptable limits at the point of location and thereby total distortion shall be contained in the system.

NOTES:

1. The magnitude of each harmonic current to be limited or to be targeted is defined in IEEE -519 Standards. The same can be followed for THDI_f calculation.
2. The design margin can be applied to accommodate uncertainty in harmonic producing loads. Further diversity factor of 0.8 may be applied for set of harmonic producing loads if applicable.

Advantage of AHF

Active Harmonic Filter is considered most economic and probably the best way for limiting the harmonic distortion in offshore Electrical Power System

In the past, passive filters were used to filter out the harmonic currents on Onshore/ Offshore facilities. Following problems / limitations were observed in the process of their use.

• A passive filter circuit may only filter one harmonic component. Therefore a separate filter circuit may be required for each harmonic to be filtered.

• It is bulky in size

• Passive filter always provide certain amount of reactive power

• Passive filter gets overloaded in the event tuned frequency harmonic current exceeds its capacity.

• The change in load or change in frequency renders passive filter ineffective.

• Passive filter may resonate with network inductance and damage the equipment.

In order to overcome all these problems/ limitations of passive filter, IGBT based Active Filter has been developed. AHF can cancel harmonics in real time by injecting exactly equal amount in phase opposition of harmonic currents whenever they arise. AHF offers following advantages:

• Total elimination of all harmonics

• Minimum space requirement

• AHF is flexible in use.

• No loading problem

• Power factor improvement can be achieved.

Conclusion

In the past design engineers did not pay much attention to the problem of Harmonics. Now due to increasing use of power electronics and other harmonic producing devices, harmonics are posing serious problems. The harmonic currents are not limited to equipment, but flow through out the power system and impact other users. Harmonics cause over current, equipment failure and power loss in the system. Voltage harmonic stresses the insulation and over current weakens it by heating which can lead to early breakdown of power equipment. There are Electromagnetic Interference (EMI) issues due to presence of high frequency harmonics.

Harmonics are considered as pollution in the electrical power system and they need to be contained. They can be contained by adopting mitigation measures as discussed in this paper. In offshore power system where space is at premium, Active Harmonic Filter is the right choice, if other equipment oriented techniques are not applied.

In conclusion if harmonic producing loads are substantial in the system (more than 10 % of total running load), a harmonic study should be conducted and mitigation measures should be applied to limit them within acceptable level. The step by step method can be applied to arrive at the AHF size during planning and initial design stage.

References**Standards and Recommendation**

- IEEE399: Recommended Practice for Power System Analysis 1997 (Brown Book)
- IEEE519: Recommended Practice and Requirements for Harmonic Control in electrical power Systems 1992
- IEEE2000: Draft guide for Application and Specification of Harmonic Filters

IEC61000 2-2: Compatibility levels for low frequency conducted disturbances and signaling in public low-voltage power supply system

IEC61000 2-4: Compatibility levels in industrial plants for low frequency conducted disturbances.

IEC61642: Industrial AC networks affected by Harmonics-application of Filters and Shunt capacitors

G.5/4: UK Electricity council Engineering recommendations

G.5/3: UK Electricity council Engineering recommendations

IEEE C57.110: Recommended Practice for establishing Transformer Capability when supplying Nonsinusoidal load current

Technical guide No.6 "Guide to Harmonics with AC drives _ABB"

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