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Application of New Generation Transformer Harmonic Filter Hybrid Solution To Reduce Footprint and Operating Cost at the well site.

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Abstract

In recent years, Electrical Submersible Pump operators are facing increasing demands to provide more economical ways of producing crude oil at the well site. One of the ways to decrease the cost of production is to reduce the cost of electrical energy used for the ESP system. The limiting of harmonics produced by ESP electrical systems to IEEE-519 recommended levels is widely used, yet greatly misunderstood, as there are a variety of methods and tools that must be made compatible with the application in order to achieve successful mitigation of the harmonics.

Increased horsepower, larger electrical ESP systems, and greater energy consumption require more space at the well site. On offshore installations, that space has always been at a premium. The footprint expansion of this ESP electrical equipment would create unacceptable costs considering the current cost-saving market conditions.

This paper presents an innovative approach to tackle harmonics mitigation. This significantly smaller and cheaper approach delivers the required IEEE-519 THDI in ESP electrical system whilst incorporating new technologies that present characteristics capable of increasing the run life of an ESP electrical system.

A typical ESP electrical system installation has usually contained the following: SDT – Step Down Transformer, HF – Harmonic Filter [or some other means of controlling harmonics], VSD- Variable Speed drive, SWF – Sine Wave Filter, SUT – Step Up Transformer, and ESP Motor. Combining the Step Down Transformer with the Harmonic Filter and designing it as a one-piece unit, cooled in oil, creates a smaller and therefore more cost-effective device, that achieves more desirable harmonics characteristics. Including not only efficient cooling, but the use of parasitic inductances of transformer windings as a useful component of the integrated harmonic filter gives an advantage on the technical market. This paper provides further discussion and details on this concept's advantages as a solution to reducing operating costs.

Introduction

Depressed oil prices on the World Market necessitate increasing focus on management of field development and operating costs. The re-visitation of surface equipment arrangement is especially important for older fields with deeper wells and where more wells have been added. The Operator requires greater VSD horsepower output to effectively exploit the reservoir, as well as, a reduced SEE skid footprint in order to keep capital costs within revised budgetary constraints.

Generally, oil fields have their own main electrical power grid established. Unfortunately, the fields require continuous addition of loads, which stretches the grid capability above its limits. To withdraw more power, loads must be carefully managed whilst their power efficiency and cleanliness are kept to a maximum.

In conventional Electrical Submersible Pump (ESP) installations, the surface equipment consists of one Step-Down transformer (SDT) connected to a skid-mounted Variable Speed Drive (VSD). Each VSD requires its own multi tap Step-Up Transformer (SUT) to raise the output voltage so to suit the ESP motor requirements for the application.

The most significant problems posed by the Middle Eastern oil fields are caused by the harsh environment. All of the equipment, namely the transformers, VSDs, and filters, must be in a NEMA 4 / 4X enclosure that protects against windblown dust and water and allows for uninterrupted operation at high summer temperatures of up to 55°C.

In an ideal power system, the voltage supplied to the equipment and the resulting load current are perfect sine waves, however, in practice, conditions are never ideal and these waveforms are often distorted. This deviation from perfect sinusoids is usually expressed in terms of harmonic distortion of the voltage and current waveforms.

Source of Harmonics

Harmonics are caused by nonlinear loads attached to the power systems, mainly large-sized Variable Speed Drives. The harmonic current caused by the nonlinear system can cause harmonic distortion in the system voltage which may cause problems for other devices. The effects of such harmonics fall into four general categories:

- Effects on consumer and industrial load: computers and computer-controlled machines are especially susceptible
- Effects on the power system itself: damaging dielectric heating is created in cables and supply transformers of the electrical grid
- Effects on communication circuits: interferences and disruptions of communication systems
- Effects on revenue billing: penalties for their presence in addition to a need for large and costly equipment to keep up with harmonic loads

To understand Input Harmonics and the techniques to mitigate them a few introductory terms need to be presented and explained.

- Harmonics is the term used to describe the shape or characteristic of a voltage or current waveform concerning the fundamental frequency in an electrical distribution system.
- Current Distortion: Distortions that create higher current peaks that can cause transformer heating or nuisance tripping by fuses, circuit breakers, and other protective devices due to the lack of rating for harmonically rich waveforms.
- Voltage Distortion: A distorted voltage has higher peak values that produce non-sinusoidal voltage drops across the distribution system. The resulting voltage drops add or subtract from the sinusoidal voltage supplied by the utility. Other utility customers could get distorted voltage on the downstream side of the power distribution circuit.

Electrical power systems rich in harmonics are generally associated with a poor power factor and low efficiency. This is due to the previously mentioned effects of harmonics in addition to the unnecessary heat they cause in the equipment they are connected to and the initiated system resonance that can severely disrupt operations of the grid.

IEEE-519-2014

IEEE-519 is a recommended guideline for designing electrical systems, NOT a mandatory standard. Harmonics is a system issue rather than any particular equipment issue. IEEE-519 sets limits on the voltage and current harmonics distortion at the point of common coupling (PCC, usually the secondary of the supply transformer).

The total harmonic distortion at the PCC is dependent on the percent of distortion from each non-linear device considering the total capacity of the transformer and the relative load of the system.
The IEEE-519 recommended practice defines “dedicated,” “general,” and “special” classifications. Hospitals and airports fit into the “special” category while most others fit in the general classification. Systems with only VSD loads are defined by IEEE as "dedicated" and allow higher distortion and are exclusively assigned to the converter load.

The IEEE-519 states that the estimated load current should be taken from one year of an average running current. If this is not known, 80% of the Full Load Amps may be used as an acceptable approximation.

This recommended guideline should not be used blindly. Owners and engineers must be educated on applying the IEEE-519 as raising costs for customers without rational clarification of the guidelines is not the optimum engineering solution.

Permissible voltage harmonic distortion limits at the connection point according to IEEE 519-2014

Voltage at PCC	**Individual Harmonics**	**THDu**
V ≤ 1kV	5,0%	8,0%
1kV < V ≤ 69kV	3,0%	5,0%
69kV < V ≤ 161kV	1,5%	2,5%
161kV < V	1,0%	1,5%

Permissible current harmonic distortion limits for all devices at the connection point depending on R_{SC} according to IEEE 519-2014

I_{SC}/I_L	**h < 11**	**11 ≤ h < 17**	**17 ≤ h < 23**	**23 ≤ h < 35**	**35 ≤ h ≤ 50**	**THDi**
< 20	4%	2%	1,5%	0,6%	0,3%	**5%**
20 < 50	7%	3,5%	2,5%	1%	0,5%	**8%**
50 < 100	10%	4,5%	4%	1,5%	0,7%	**12%**
100 < 1000	12%	5,5%	5%	2%	1%	**15%**
> 1000	15%	7%	6%	2,5%	1,4%	**20%**
I_L – max. Load current at the connection point; Isc - max. Short-circuit current at the connection point;						

Figure 1: IEEE-519-2014 Distortion Limits for General Distribution Systems

PCC - Point of Common Coupling: Point where harmonic measurement is to be made and typically where the utility power is connected. Also defined as the point where non-linear load meets the linear load within a plant – most popular definition used by Consultants to enforce Drive Manufacturers to meet IEEE519 at VSD input.

TDD – Total Demand Distortion: Harmonic current distortion in percent of maximum demand load current. The maximum demand current interval could be either a 15-minute or a 30-minute interval.
ISC: Short-circuit current at PCC: Defines the size of the Customer's load from Utility's viewpoint.
IL: Maximum demand load current at the fundamental frequency.

IEEE should be applied at the system level and may have impacts as utilities charge penalties for harmonically rich waveforms generated on the grid.

Standard Harmonics Mitigation Solution

The problem of mitigating harmonics is widely recognized in many industries where large power drive systems are used. Drive systems over 100kW are considered large and produce a large amount of unwanted harmonic noise which is sent back to the electrical grid. Power companies are implementing penalty fees that force customers to keep their end of the grid clean. Various industries have different requirements and methods of dealing with the problem and in effect many solutions. These include the following currently used solutions:

Active Solutions:

- AFE Active Front End Drives solution to reduce harmonics THDI @ PCC to approx. 4-6%
- Active Filters solution to reduce harmonics THDI @ PCC to approx. 4-7%

These are expensive due to electronic circuits and components increasing maintenance and repair cost. These solutions use standard distribution or separation transformers but are not particularly suited for the O&G Industry. Especially AFE systems, in which return of energy to the grid is not practical and large inductors require additional cooling.

Less popular Active Solutions:

- Boost Converter Topology – Inherently regenerative: The large size and expense, as well as, the EMI conducted are of concern.
- Non-regenerative type: Injects the current from the conducting phase to the nonconducting phase using semiconductor switches.
- Shunt type: Monitors the load current and injects identical load current so that the harmonics cancel out.

These are customized solutions, not available as a standard product.

Passive Solutions:

- Passive Filters - reduce harmonics THDI @ PCC to approx. 5-10%

These filters are very popular and a widely used solution not only in the O&G Industry due to being cheap and simple to install. They are load dependable but typically only loads over 60-70% can guarantee 5% THDI.

- AC Line Inductors (Reactors).
- DC Link Chokes or DC Bus Inductor

Chokes and Inductors are usually provided by drive manufacturers as an option, important for the proper and smooth operation of drives. Operators attempt to save on costs by eliminating such essential components, when inductance plays a vital role in the electrical scheme of the system and should be a standard component for every drive, despite additional filters or other harmonic mitigation components.

Multi-pulse / Preventive Solutions:

- 12 pulse VSDs /three-winding isolation transformer / or Pseudo 12-pulse / Autotransformer base scheme = 15% - 20% THDI.

This is an internationally popular, cheap, and technically sensible solution. The transformers are easily built, symmetrical, and require only cheap wiring. Almost every large power drive over 100KVA is designed in 12 pulse configurations, making the solution economically, and technically reliable.

- 18 pulse VSDs / four-winding isolation transformer / or Pseudo 18-pulse / Autotransformer base scheme = 8% - 12% THDI.

An uncommon solution due to the difficulty of manufacturing an 18-pulse transformer of good quality. Additionally, only a few suppliers of 18-pulse drives are currently on the market.

- 24-pulse VSDs / five-winding isolation transformer / below 5% THDI.

A very effective and clean solution however rarely used as a means to reduce harmonics, as currently, only a few Oil Companies in the Middle East are using it as a standard because of the high cost and limited pool of vendors that are able to supply good quality drives and transformers.

Description of the Solution

Every Oil Field Surface Electrical Equipment installation faces the challenge of delivering a system that meets the customer's electrical specification, whilst minimalizing its package, cooling it, and maintaining a reasonable price.

Incorporating two of the above-mentioned solutions: the Advanced Passive Filtering with the 12-pulse oil-immersed and hermetically sealed transformer design into one Hybrid unit creates new technology and a solution to this challenge.

By using a leakage inductance of the 12-pulse transformer, together with the auxiliary resonant trap of the filter, the harmonics which are present in the standard twelve-pulse solutions can be suppressed.

The characteristics of the solution depend, to a large degree, on the geometric design of the transformer and magnetic design of the filter. In order to understand the behavior and to optimize the performance analytical, magnetic, and electrical models were developed and used to design the prototype.

By combining two harmonic suppression mechanisms we are resolving numerous issues.

The first is the problem of cooling large size inductors in the filter's assembly. Every standalone Harmonic Filter requires a large size enclosure to be able to cool and dissipate heat through its walls. Very often external fans or Heat Exchangers are used to resolve this issue. It is the main reason for many failures in Surface Electrical Equipment in the field, especially in the Middle East. The system needs to be able to operate in harsh summer conditions where temperatures in the field can average 55°C in June and July. By submerging the filter in the transformer oil, the cooling system of the transformer takes care of all additional heat loses.

Secondly, all wiring between the transformer and filter is internal within this assembly, which eliminates costly wiring and hours of labor during installation. All capacitors are mounted in the additional enclosure on the side of the transformer, allowing easy maintenance access for routine inspections or replacement.

Thirdly, filter inductors are calculated as a part of the transformer-filter unit, using its parasitic inductance of the windings as a common part of the whole integrated harmonic system. This reduces the size of the inductance and cost of windings. Filter parameters are easily calculated and tuned for particular systems.

Additionally, if used as a separating multi-pulse transformer-filter for generator-powered systems, it presents a very low No Load Capacitive Current, that is below 5%. Anyone who has ever worked with generator-powered Surface Electrical Equipment will appreciate this in the future.

This Hybrid offers greater power efficiency with a smaller footprint (of at least 10%-20% smaller than conventional Step-Down Transformer plus Harmonic Filter), producing fewer harmonics (below 5% THDI for loads above 45%) and an environmentally isolated NEMA-4/NEMA-4X for the Step-Down Transformer.

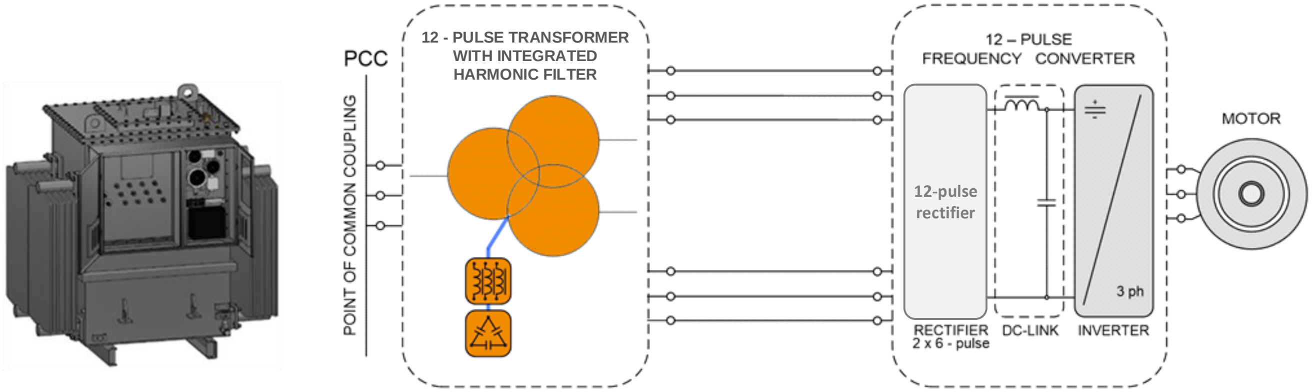

Figure 2: Transformer Harmonic Filter Hybrid General Description

Typical characteristics for THF-Hybrid:
- Oil-immersed, hermetically sealed, 12-pulse transformer with integrated harmonic filter
- Solution combines two harmonic suppression mechanisms:

12-pulse rectification & Advanced Passive Harmonic Filtering

THD of the input current:	< 5% for load above 45%
Lagging input current:	Load above 30%
Leading input current:	Load below 30%
No load capacitive current:	< 5%

Parameter	External HF	Hybrid THF	Advantage
THD (input current)	6-8%	< 5%	Better
No load capacitive current	< 40%	< 5%	Much better
Lagging input current	Load above 60%	Load above 30%	Much better
Drop voltage	10-16%	<5%	Much better
Losses*	11,200	9,500	Saving 15%
Weight*	5,400	4,200	Saving >20%
Cost*	$114,000	$99,000	Saving 13%

“ * ” Calculated for 600KVA compatible systems

Figure 3: Advantages of THF-Hybrid over standard 12-pulse transformer with external harmonic filters set-up.

Simulation and Tests Result

Since the beginning of 2018, simulations and calculations were made to see, if the construction and characteristics were economically worth proceeding with a project. Financial aspects were considered alongside electrical parameters: required THD limits, cooling, sizing, the complexity of construction, and manufacturing issues.
In February and May of 2019, two prototypes were built and tested to compare mathematical simulations and prove characteristics of the Hybrid. These provided further understanding into the imbalances of the drive systems, soft grids, and grid inherited harmonics, as well as, a variety of other smaller issues that have an immense impact on the final result.
Many measurements and characteristics were taken so to continue research and propose commercial products. The results were better than expected.
If looking exclusively at THDI – for loads above 45% we can guarantee 5% THDI. [Fig.XX]. Which is better than any average passive harmonic filter on the current market. Power coefficient as a function of load also stands out – as shown in Fig. XX.

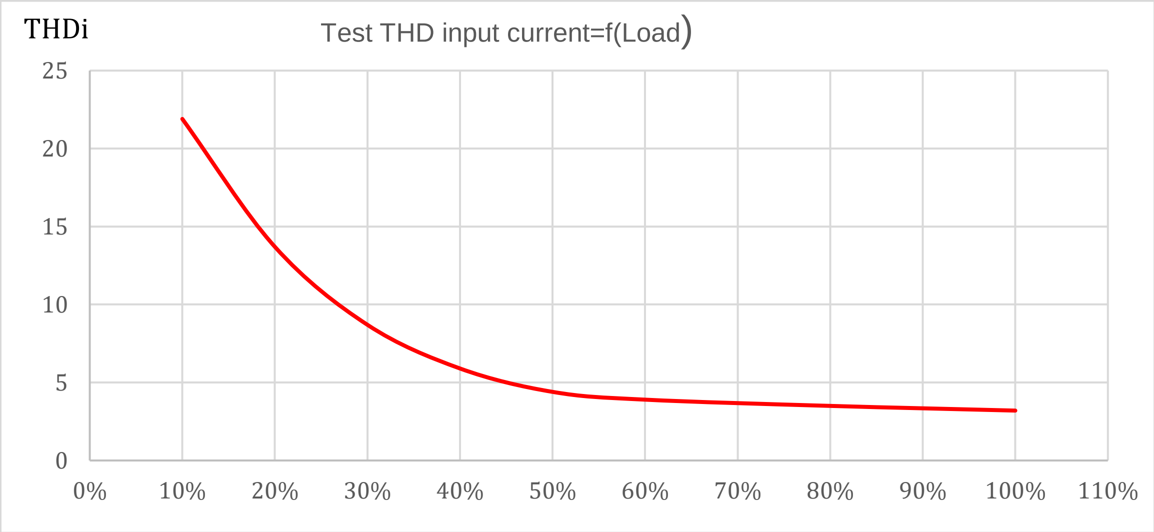

Figure 4: Test results for THDi as a function of load.

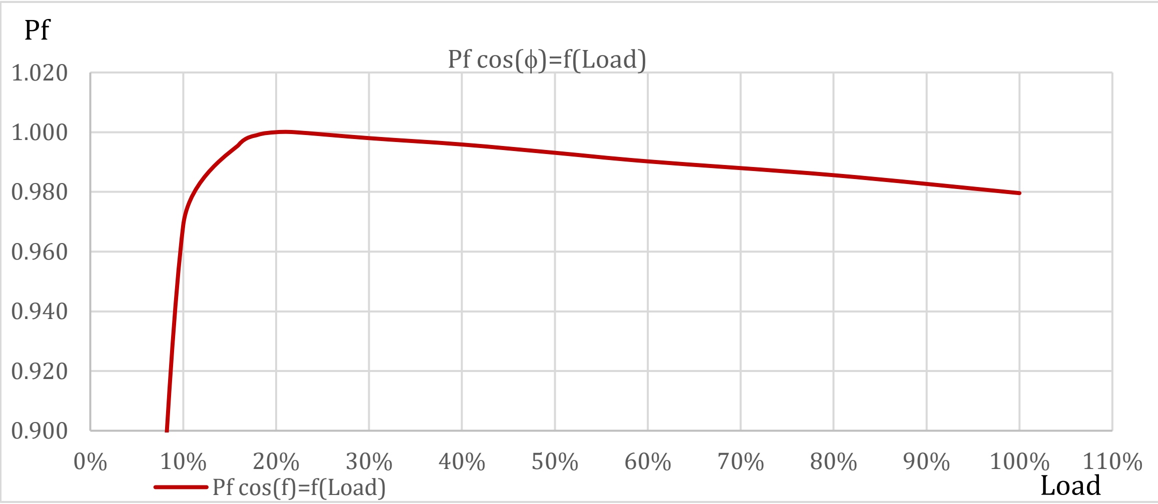

Figure 5: Test results for Power Coefficient as a function of Load

Test results comparing the mathematical simulations and test measurements are presented in Fig. 6. This comparison proves the ability to calculate and build a desired Hybrid for any customer requirements.

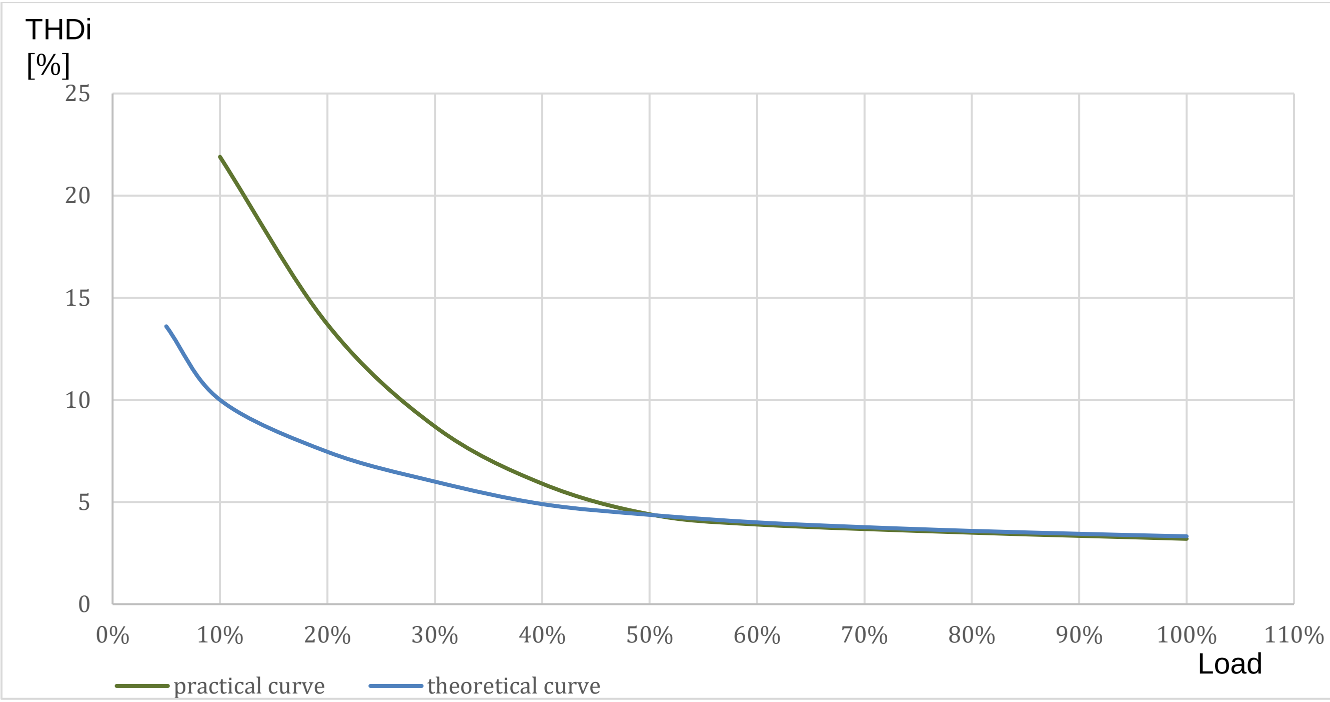

Figure 6: Comparison of mathematical simulation and real test results for THDi as a function of load.

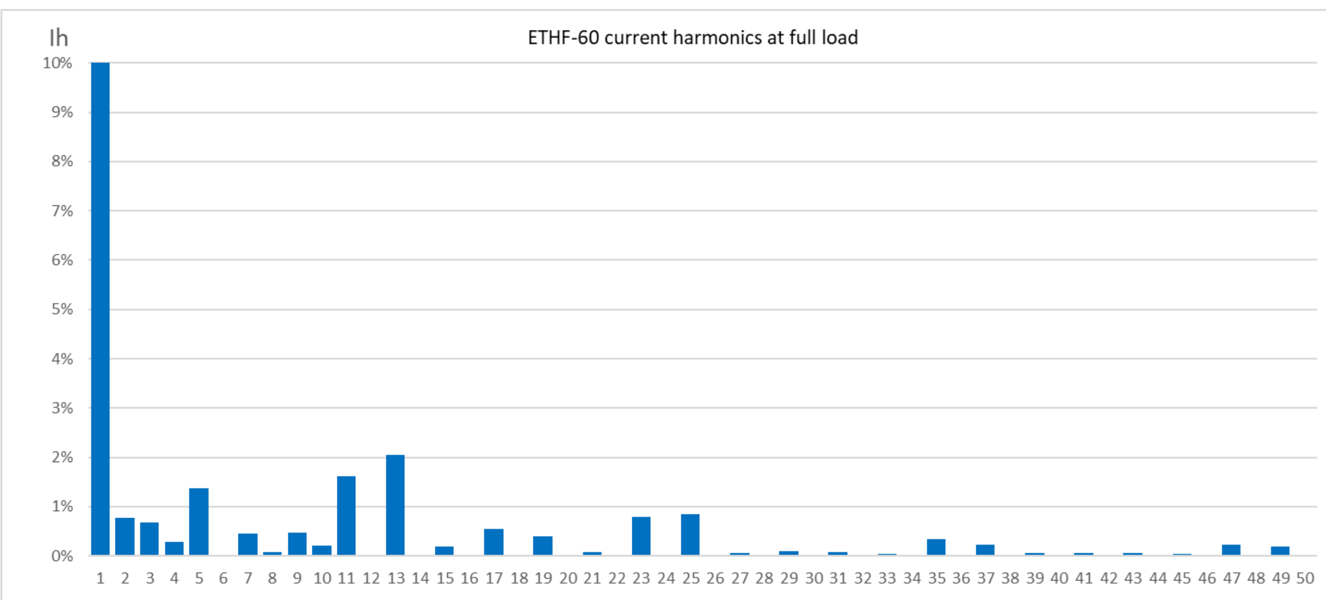

Figure 7: Harmonics Spectrum up to 50 at full load

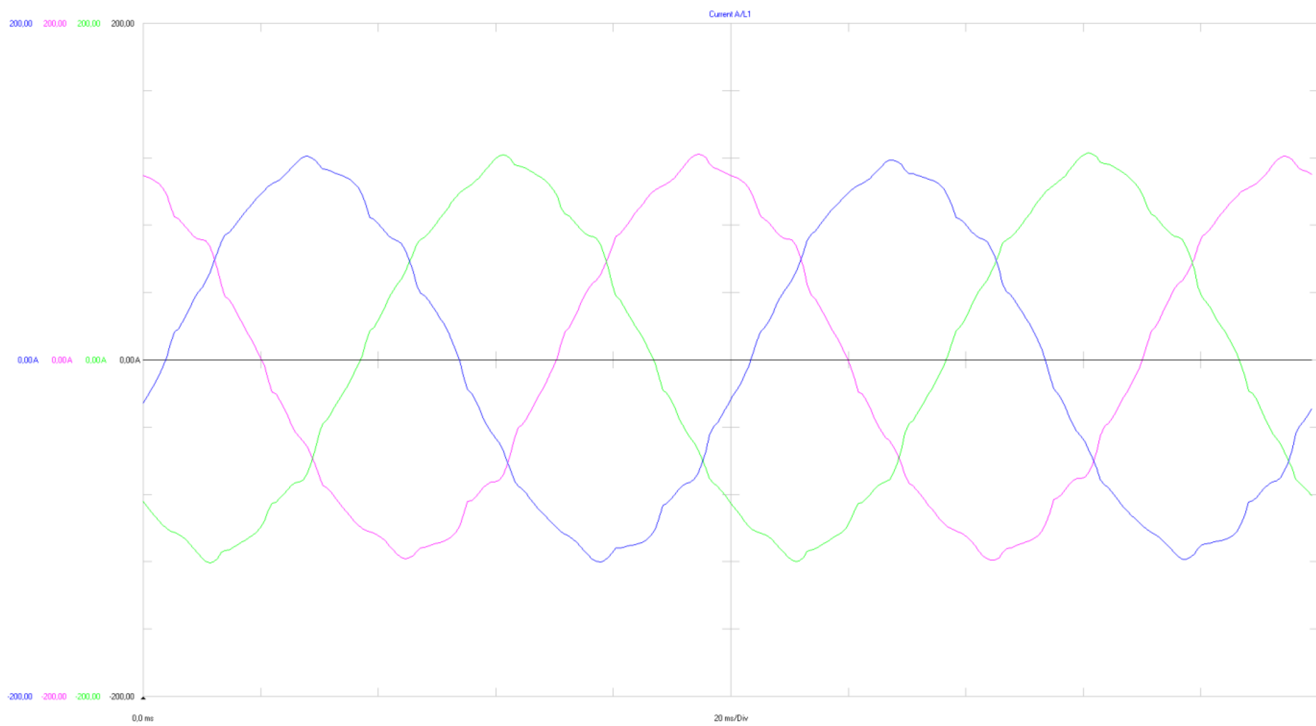

Figure 8: Input Current at the full load

Field Trial

Two prototypes were built for testing the idea, checking characteristics against mathematical simulations, and in preparation for this article. The first true field trial will be done by the end of 2019 with one of the major ESP companies in the Middle East.

Conclusions

The negative effects and costs caused by the occurrence of harmonics in the Variable Speed Drive's input current are an obvious problem encountered by Operators of the oil fields today. The necessity of enlarging all electrical components working with VSD systems, additional power losses, interferences, etc., forces field operators to limit emissions of the harmonics effectively.

The concept of Transformer-Harmonic Filter Hybrid solution presents a valid method for Surface Electrical Equipment system to:

- decrease harmonics, into IEEE-519 - 5%THDI level
- decrease footprint and weight on offshore/onshore installations
- increase total system efficiency
- decrease the total system cost

This new generation of harmonics mitigation technology will result in significant cost savings for Operators in terms of Capital and Operating Expenditures. Harmonic mitigation on the supply side of the VSD has reduced the risk of penalties. Additionally, the power quality can result in an extended run life for the transformers as well as the whole oilfield - the ultimate goal for offshore/onshore applications.

Design-oriented modeling and simulation predict results and prove the validity of the developed models and design procedures. Practical design procedure of the THF-Hybrid is ready for the manufacturing process and field implementation.

This kind of new approach was never used before, as transformer manufacturers do not build filters, viewing such an operation as a threat to their business. Manufacturers of the passive filters are continuously designing increasingly better filters; however, they constantly face problems with packaging

and cooling units. Drive manufacturers prefer to resolve harmonic issues by adding sophisticated electronic circuits and have no interest in working with choke and inductor manufacturers.
By combining both ideas into one device a better system efficiency can be achieved at a smaller size and lower cost.

Disclaimer

Technical design details are not part of this article and will not be disclosed. This Transformer – Filter Hybrid solution application and design is patent pending.

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Nomenclature:

ESP – Electric Submersible Pumps
SEE – Surface Electrical Equipment
SDT – Step Down Transformer,
HF – Harmonic Filter,
VSD – Variable Speed drive,
SWF – Sine Wave Filter,
SUT – Step Up Transformer,
THDI – Total Harmonic Distortion of Current,
PCC – Point of Common Coupling,
AFE – Active Front End Drive

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