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A Comparative Study on Power System Harmonics for Offshore Plants

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해양플랜트 전력시스템의 고조파 비교분석에 관한 연구

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Abstract : *The field of power system harmonics has been receiving a great deal of attention recently. This is primarily due to the fact that non-linear (or harmonic-producing) loads comprise an ever-increasing portion of what is handled at a typical industrial plant. The incidence rate of harmonic-related problems is low, but awareness of harmonic issues can still help increase offshore power plant system reliability. On the rare occasion that harmonics become a problem, this is either due to the magnitude of harmonics produced or power system resonance. This harmonic study used an electrical configuration for the offloading scenario of a Floating LNG (FLNG) unit, considering power load. This electrical network configuration is visible in the electrical network load flow study part of the project. This study has been carried out to evaluate the performance of an electric power system, focusing on the harmonic efficiency of an electrically driven motor system to ensure offshore plant safety. In addition, the design part of this study analyzed the electric power system of an FLNG unit to improve the safety of operation and maintenance.*

Key Words : *Active Front End (AFE), Floating Liquefied Natural Gas (FLNG), Switch Mode Power Supply (SMPS), Total Harmonic Distortion (THD), Variable Frequency Driver (VFD)*

요 약 : 해양구조물에 전기 안전사고가 급증하면서 전력시스템 고조파 분야가 최근 많은 관심 받고 있다. 이것은 주로 비선형 (또는 고조파 생성) 부하가 일반적인 산업플랜트 전력시스템에서 계속 증가되고 있기 때문이다. 해양플랜트에서는 전력시스템의 안전설계로 인하여 고조파 문제의 발생률은 낮지만, 고조파 문제에 대한 인식은 전력시스템 설계의 신뢰성을 향상시키는데 여전히 도움이 될 수 있다. 전력시스템에 고조파 문제가 드물게 발생되는 경우, 이는 생성된 고조파의 크기 혹은 전력시스템의 공진 때문이다. 이 고조파 비교분석에 관한 연구는 전력부하를 고려한 부유식 액화천연가스 생산·저장·하역 (FLNG) 설비의 하역 운전 시나리오에 대한 전기적인 구성으로 비교분석하였다. 전기적인 네트워크 구성은 전기적인 네트워크 부하 흐름에서 볼 수 있다. 본 연구는 해양플랜트 전력시스템의 안전을 보장하기 위해 전기 모터 시스템의 고조파 효율에 초점을 맞추어 전력시스템 성능을 시뮬레이션을 통해 검증하였다. 또한, 본 연구의 설계분야에서도 운전 및 유지·보수의 향상시키기 위해 FLNG 설비의 전력시스템을 분석하였다.

핵심용어 : AFE, 부유식 액화천연가스 생산·저장·하역 설비, 스위칭 모드 전원공급장치, 고조파, 가변주파수장치

1. Introduction

Power system harmonics is a distortion of the normal electrical current waveform, generally transmitted by non-liner loads. Switch-mode power supplies (SMPS), Variable Frequency Driver (VFD) and electrical motors, photocopiers, personal computers, laser printers, fax machines, battery chargers and UPSs are examples of non-liner loads. Single-phase non-liner loads are prevalent in modern office building and offshore projects, while three-phase, non-liner loads are widespread in factories and industrial plants.

A large portion of the non-liner electrical load on most electrical distribution systems comes from SMPS equipment. For example, all computer systems use SMPS that convert utility AC voltage to regulated low-voltage DC for internal electronics. These non-liner power supplies draw current in high-amplitude short pulses that

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create significant distortion in the electrical current and voltage wave shape-harmonic distortion, measured as Total harmonic distortion (THD). The distortion travels back into the power source and can affect other equipment connected to the same source (Bose, 1997).

Most power systems can accommodate a certain level of harmonic currents but will experience problems when harmonic currents flow through the power system, they can cause communication errors, overheating and hardware damage such as;

· Overheating of electrical distribution equipment, cables, transformers, standby generator, etc
· High voltages and circulating currents caused by harmonic resonance
· Equipment malfunctions due to excessive voltage distortion
· Increased internal energy losses in connected equipment, causing component failure and shortened life span
· Generator failures

2. Method for the Harmonic Analysis

The currents absorbed by power electronics loads - currents that are not perfectly sinusoidal - are decomposed in their harmonic components by means of Fourier Analysis. Once the base frequency (60 Hz in this floating offshore unit) absorbed power is given, and consequently the 1st harmonic (60 Hz) current is know, the currents at the highest frequencies can be given as a percentage of the 1st harmonic one. The phase shift between each higher harmonic and the 1st one is also needed for the studies (it’s also obtained by Fourier Analysis) in case the superposition of multiple harmonic sources is to be represented (Arrillage et al., 1997).

The harmonic contents of a waveform is typically called harmonic spectrum and consists a table with the values of the amplitude and phase angle for each single harmonic.

For typical and balanced loads, the only significant harmonic levels (harmonic orders) are the ones with h = 1, 5, 7, 11, ... or $h = 6 \cdot m \pm 1$, where h = is the ratio between the frequency at each harmonic and the base frequency (i.e. h = 5 means F = 300 Hz, when the base frequency is 60 Hz). Even harmonics are normally not produced by the power electronic loads, as well as the harmonics multiple of 3 (3, 6, 9, ...), since the correspond to zero sequence current systems.

The harmonic 1, 7, 13, ... $6 \cdot m+1$, ... correspond to positive sequence current systems, while the harmonics with h = 5, 11, 17, ..., 6 m-1, ... correspond to negative sequence current systems.

The 1st harmonic voltages and currents in the system are obtained by means of a normal 60 Hz load-flow calculation. The higher harmonic orders currents of the harmonics loads are then considered as current sources and are injected, for each harmonic order, in a network model that represent the system response at the correspondent frequency. A liner and direct calculation at each harmonic level (independently) is then performed, allowing to obtain the current distribution for that harmonic in all the branches and the voltage amplitude for that harmonic in all the bus bar.

The system representation can be moved, including the consideration of the skin effects for cables and rotating machines resistance and reactance. This allow to obtain much more realistic results.

Typically, the considered harmonic level ranges from h = 1 to h = 49. Higher harmonic orders are usually neglected, both for the reason that they are usually very small, and for the fact the system response at such high frequencies depends upon non-linear effects (skin effect, etc) that are in some measure unpredictable and anyway the resistive effects are usually very high and avoid dangerous resonances.

The injected current amplitude in general decreases for higher values of h, but the possible presences of resonance frequency is the system must be carefully considered. In fact, at some frequency the system response - that is, finally, the system impedance seen from the injection point- could have a peak with a very high value (IEC61000-3-2, 2014).

3. Model for Harmonic Studies

The model for this harmonic studies is using the electrical configuration of the Offloading scenario on offshore unit. This configuration of the electrical network is visible in the Electrical network load flow study.

The Booster Compressor and one (1) Thruster are simultaneously supplied from three (3) Gas Generators.

The only difference comes from the fact that all loads (damping terms) were removed. Only the involved power supplies and harmonic sources were left active, i.e. the VFD of the booster and the VFD of the Thruster.

All energy of Case 1 comes from the 3 Gas Generators coupled at 13.8 kV level.

The exam of the voltage THD at total no load is destined to get the ultimate highest prospective values for the voltage THD itself and its harmonic ranks. By the way, this also makes this study almost entirely ‘universal’ regarding situations / scenarios where variable speed might be used. This pessimistic care is also destined to take care of synchronous generators involved to supply these harmonic loads: The ratio “Number Of Winding Turns of the main Field Winding” / “Number Of Winding Turns of the Stator Winding” is generally in a range between 20 to 30.

Consequently, a 1 Volt pulse applied to the stator may become a 20 to 30 Volt pulse at field-rotor winding level, resulting in a di-electrical stress.

The voltage THD that is obtained is maximized because of the total absence of damping terms coming from liner loads which are inhibited here (Elgerd et al., 1998).

3.1 Case 1: Harmonic study for Low load condition

The considered technology for this VFD is AFE (Active Front End) with a switched input bridge.

The harmonic cancellation by mitigation being more easily obtained by a multiplexed energy consumption on the 3 phase than by a substraction of harmonic consumptions between secondary windings regularly phased.

The considered technology for this VFD is a common 24 pulse without a switched input bridge (Diode Front End). This choice is guided by the two following reasons:

- The variable speed of thrusters is generally obtained with a long time experienced technology.
- The driven power is relatively weak and so have a low impact in terms of distortion.

Consequently, the 24 pulse choice is the best compromise:

A low requirement in terms of harmonic content on any source, even a sensitive synchronous generator and a longtime experienced technology.

The booster VFD is modelled as follow;

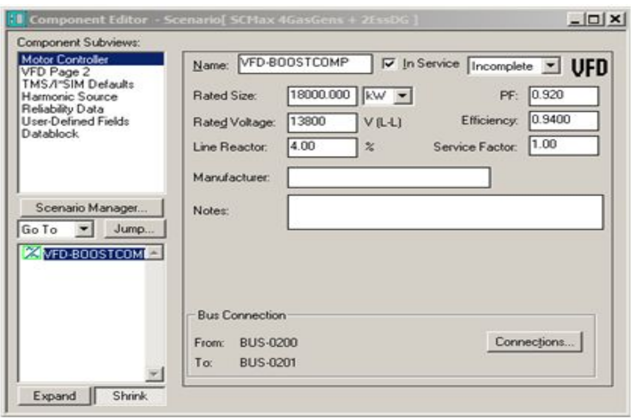


Fig. 1. Booster VFD Specification (Simulation data).

The following spectrum has been used (obtained in a worldwide supplier catalogue). It has to be noticed that ranks over 25 (i.e. ranks 29 to 41) where artificially emphasized with a 0.11 % value in order to bring the global THD up to rank 41 equal to 5 %. 5 % being the ultimate THD value in current absorption of the AFE technology.

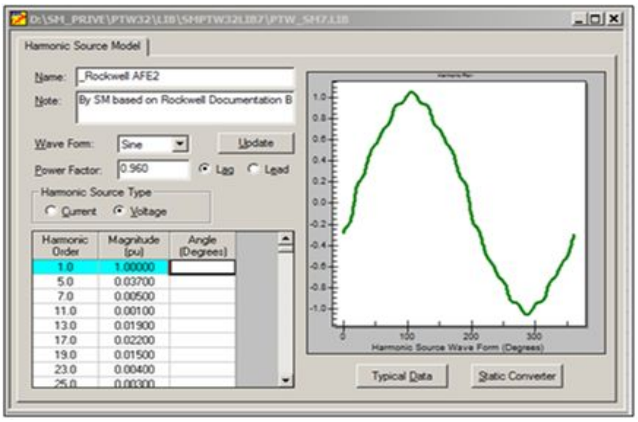


Fig. 2. Spectrum wave for Booster VFD.

Power factor 0.96 is the intrinsic power factor of the electronic chopping unit, while 0.92 in above VFD dialog box is there to take into account the presence of 4 % line reactor. The presence of padding ranks 29 to 41 is visible in above screen shot for voltages close to +1 and -1.

The Thruster VFD is modelled in Figure 3.

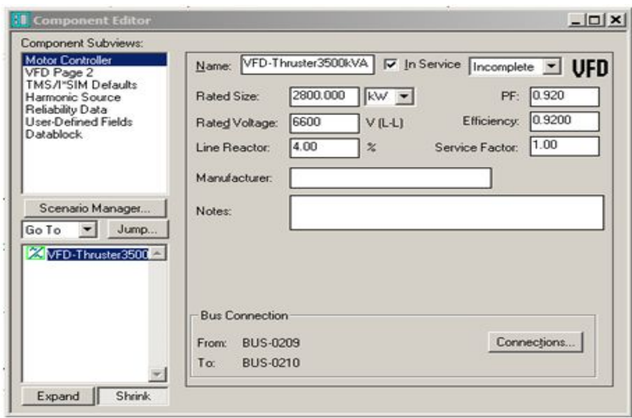


Fig. 3. Thruster VFD Specification (Simulation data).

The following IEEE spectrum has been used (obtained in with embedded library of Power Tools). It has to be noticed that ranks over 25 (i.e. ranks 29 to 41) were artificially emphasized with decreasing values in the range of 0.9 % to 0.4 %. This is destined to bring the global THD up to rank 41 equal to 4 %. 4 % being the ultimate THD value in current absorption of the 24 pulse technology.

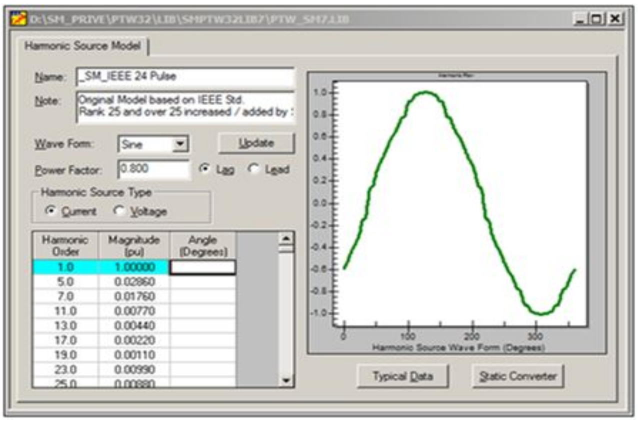


Fig. 4. Spectrum wave for Thruster VFD.

Power factor 0.8 is the original power factor of the electronic chopping unit as originally librarized, while 0.92 (in place of usual 0.96) in above VFD dialog box is there to take into account the presence of 4 % line reactor. The efficiency is lowered to take into account the presence of special transformers with multiple secondary windings. Ranks n° 29 - 41 presence is visible in irregularities.

3.2 Case 2: Harmonic study for High load condition

The model for this harmonic study is using a fictitious stringent configuration where one thruster should be run from one single essential diesel generator. This could be the case during “commissioning-trouble shooting” or startup.

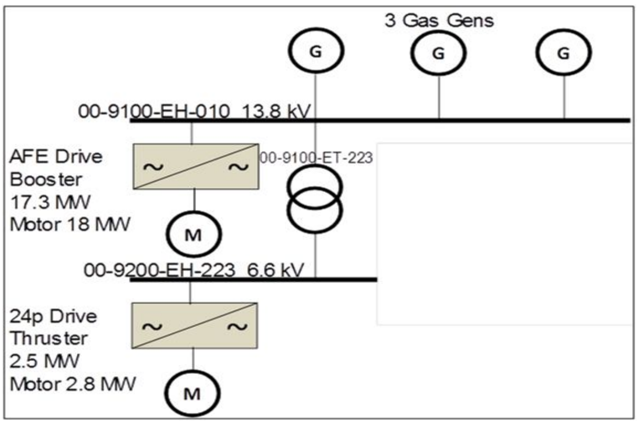


Fig. 5. Case 1 - Network configuration on Simplified Single Line Diagram.

In this case, only 1 Essential Diesel Generator located at 00-9200-EH-221 Switchboard level (6.6 kV) will supply a 2.5 MW thruster (2.8 MW) motor located at 00-9200-EH-223 Switchboard level (6.6 kV). This case being also studied at total no load (for previously listed reasons) can be made more interesting and can deliver more information.

This is the reason why the 3 Gas Generators are lst active and isolated on their own 13.8 kV level, still supplying the 17.3MW Booster Compressor.

Finally this case will embed two studies:

(1) Main Study : 1 Thruster supplied from 1 Essential Diesel Generator at 6.6 kV level

(2) Auxiliary Study : 1 Booster supplied from 3 Gas Turbine Generators at 13.8 kV level.

The voltage THD that is obtained is maximized because of the total absence of damping terms coming from linear loads which are inhibited here.

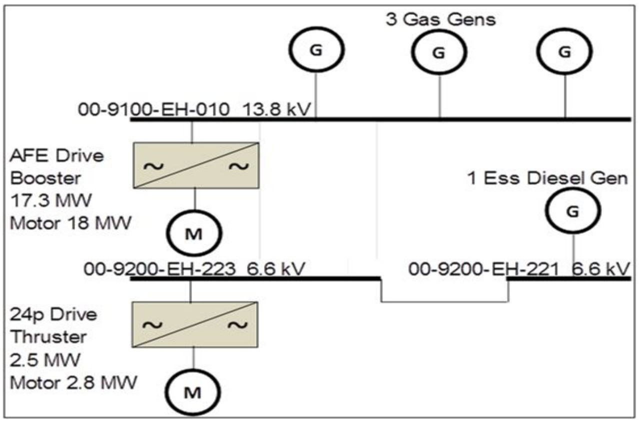


Fig. 6. Case 2 - Network configuration on Simplified Single Line Diagram.

4. Simulation Result

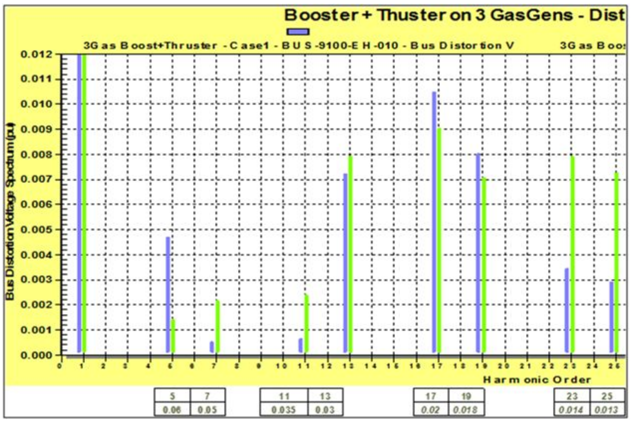
The harmonic simulation study has been peformed with the maximum number of VFD connected and address the specific harmonic distortion specification to consider in the Variable Frequency Driver selection with regards to electrical power quality. The calculation results provide the maximum acceptable spectrums for each harmonic rank according to the system frequency response.

The objective of minimizing weight and spaces associated to standard harmonic filters lead to the selection of High Frequency bridges and at least 12 pulse input transformers (Kim et al., 2014). The calculations results of this study open a large possible choice of VFD technology and vendors. Whenever, the simulation is performed with the selected and guaranteed spectrums during execution phase with vendor to validate the technology selected associated to the driven machine and speed range of operations.

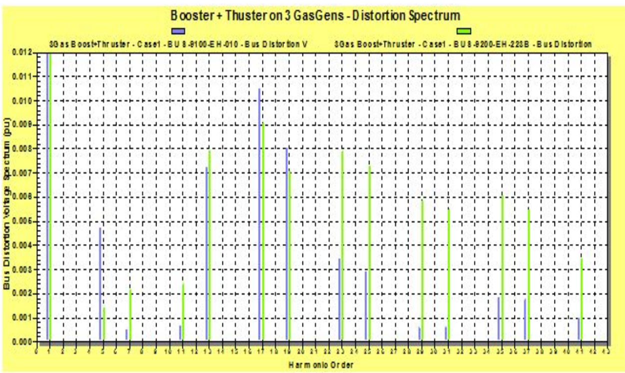
The results of simulation for each case are shown in Figure 7 and 8.

All IEC61000-3-6 are greater than 1.1 %. Figure 7 (b) and 8 (b) are close up on IEC 61000-3-6 harmonic ranks (IEC61000-3-6, 2008).

It gives the recommended practice for electric power system engineering for offshore unit to control the harmonic distortion which might otherwise determine electric power quality and safety. Each load condition is to be used as a guideline in the design of power system with non-liner loads. The limits set are for steady-state operation and are recommended for "worse-case" conditions (Gőnen, 2007).

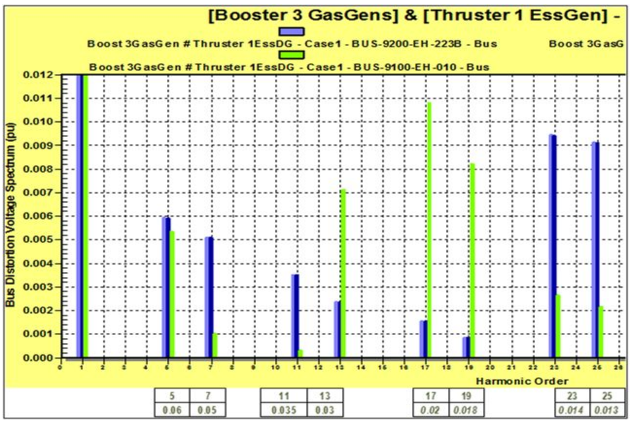


(a) Result

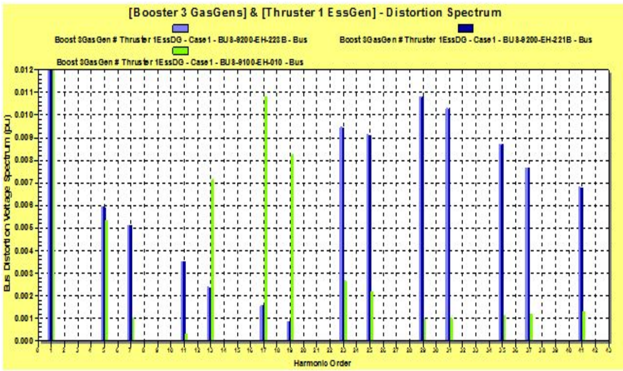


(b) Close-up

Fig. 7. Simulation result under low load condition.



(a) Result



(b) Close-up

Fig. 8. Simulation result under high load condition.

5. Conclusion

By comparison between low load power condition (Case-1) and high load power condition (Case-2), one can see that the VFD of 1 thruster (6.6 kV level) has a negligible influence at 13.8 kV level. This is due to 20 MVA transformers reactance which value is 0.14 pu.

The 13.8 kV voltage THD remains unchanged: 1.6 %

The subtransient short circuit power is slightly lower at 6.6 kV level when the comparison is achieved between one 20 MVA transformer and one Essential Diesel Generator.

When supplied from the transformer, the voltage THD is 2 %.

When supplied from the diesel generator the voltage THD is 2.6 %.

All voltage THD are remaining frankly below the authorized 8 % long term limit of the IEC 61000-3-6.

All prospective voltage harmonic ranks are also below their own individual limit recommended by IEC 61000-3-6.

This is remarkable keeping in mind these harmonic studies were achieved without damping terms that would come from supplied motors in parallel with harmonic loads.

The choice of an AFE technology for the booster is the best technical choice aboard a ship in terms of harmonic flow, global weight, surface and heat dissipation.

The choice of the 24 pulse technology has been proven to keep the harmonic ranks below their authorized limit and to reduce the “voltage pikes” stress applied to essential diesel generator.

The result of simulation for each load condition can be achieved to application of electric power system on offshore unit.

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