DESIGN OF AN ALL ELECTRIC FPSO WITH COMBINED CYCLE AND HIGH POWER VSD

Paper No. PCIC energy EUR24_11

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Abstract - To reduce Greenhouse Gases (GHG) emission, All Electric FPSO solution has been designed considering dynamic equipment driven by electric motors. The next challenge is to supply the large electric power demand at deep water and far from shore locations and, at the same time, reduce the power generation emissions responsible for 60-70 % of the total unit emissions. In this scenario, a high capacity FPSO with a combined cycle power generation plant is being designed to supply the FPSO 130 MW power demand. Variable Speed Drives (VSD's) were considered for the large electric motors to enable motor starting, besides the speed control. This paper studies the technical challenges related to designing the electric power system with combined cycle for this offshore production unit and presents the analysis and topology to accomplish technical feasibility for the electric power system.

Index Terms — GHG, All Electric, FPSO, Combined Cycle, VSD.

I. INTRODUCTION

The change in regulatory environmental regulations in Brazil in 2021 [1] gave rise to the development of new FPSO electric power system topologies capable to supply power demands over 100 MW [2]. Therefore, mechanical loads previously driven by turbines were upgraded to be driven by electric motors [3], whose speed is either controlled by hydraulic coupling or power electronic based solutions. However, the advantages of electrification in the offshore facility and the use of electric motors instead of turbo driven machinery concentrated the GHG emissions in the power generation plant.

Electrification based solutions, as Power from Shore or Power from Wind, are still under development for deep water applications, i.e., for locations with water depth ranging from 1,500 m to 3,000 m, and their application are not expected to be available in the near future (before the next 5 years).

To meet the company agreements for GHG emissions (achieve portfolio limit of 15.0 kg_{CO_2e}/boe by 2025, maintained at 15.0 kg_{CO_2e}/boe by 2030 [4]) and to cope with financeable restrictions for O&G industry, it is necessary to find different solutions for the current projects in development. Two main approaches have been taken: to reduce power system generation emissions and to improve overall driven equipment efficiency.

Since power generation in offshore units is done by gas fired turbogenerator units, and they are responsible for 60-70 % of the FPSO emissions, they became the focus of the GHG reduction studies. Since there is no alternative for this type of power source, to make it more efficient is the main goal. The use of combined cycle power plant in an offshore unit was the chosen solution, based in previous experiences (refer to [4]).

The other approach to reduce GHG is the application of more efficient equipment or solutions. To achieve this, the main compressors are driven by electric motors controlled by VSD's [6].

Next, the challenges and the advantages of using these solutions will be discussed.

II. THE USE OF COMBINED CYCLE POWER PLANT IN OFFSHORE UNITS

As mentioned before, the use of combined cycle power plant in an offshore unit can be one of the solutions available for reducing the GHG emissions in the turbogenerators exhaust. In this case, the FPSO unit load demand was around 130 MW, and being an "*All Electrical Unit*", no turbine driven load was used. To meet this demand, 5 gas turbine generators were necessary (28 MW to 33 MW), with one as a stand-by unit. However, for reducing GHG emissions, one of them was replaced with a steam turbine generator. From this point on, gas and steam turbine generators are referred to as GTG and STG, respectively.

A. THE DESIGN OF THE FPSO UNIT

The Unit considered for the design was a new build to provide production support for a brownfield, i.e., a field whose oil or gas accumulation has matured to a production plateau or even progressed to a stage of declining production. This unit will be an All Electrical, with 13.8 kV main busbar divided into two sections by a tie circuit breaker and a pyrotechnical current limiter device (see Figure 1). The other voltage levels available will be 6.6 kV and 0.69 kV. Some specific purpose loads are connected to either 0.48 kV, 0.22 kV_{AC} or 0.22 kV_{DC}, and there are also control and automation purpose voltage levels.

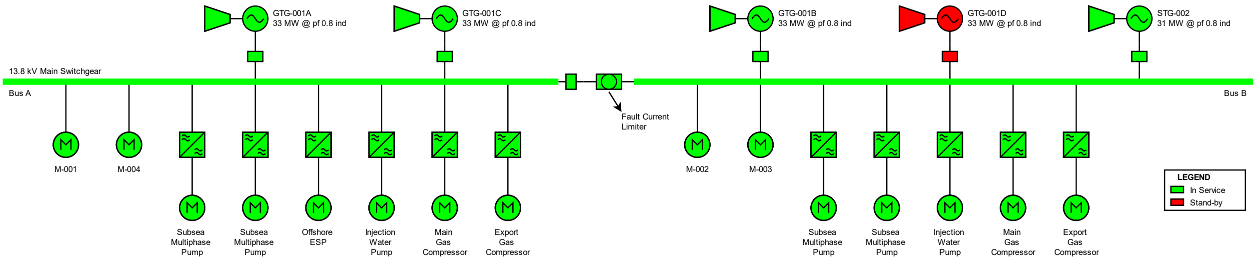

Figure 1: Simplified FPSO Unit Electrical Diagram.

B. COMBINED CYCLE POWER PLANT FOR OFFSHORE FACILITIES

The use of combined cycle power plant for onshore applications is broadly known, where the heat exhaust from gas turbine(s) is used to produce steam to drive another turbine. In offshore applications there are some differences.

For offshore applications, the main difference is that the gas exhaust is typically used for Waste Heat Recovery Units (WHRU) to heat water to be used into oil and gas production plant. If the produced gas has a lower heat capacity, the remaining heat exhausted from WHRU may not be enough to power a steam turbine sized for the needed demand. Supplementary gas fired units may be required, however this may not be the most efficient way for optimizing GHG emission reduction.

Therefore, the available electric power that a steam turbine can generate will vary along time and is lower than its full capacity, because of heat surplus from the process plant. In our design case, the STG available power is in the range of 21.0 to 28.0 MW.

Also, another critical parameter that impact the available output power is ambient air temperature. In a cooler weather (15 °C), the GTG are more efficient, but the exhaust heat temperatures will be reduced, reducing the available STG output electric power.

And it shall be highlighted that different Classification Society rules for STG are applicable [7] [8].

III. SYSTEM PERFORMANCE AND DYNAMICS USING COMBINE CYCLE POWER PLANT

A. LOAD FLOW – SHORT-CIRCUIT – STARTING MOTORS ELECTRIC STUDIES

What would be the impact of electric generators driven with different type of prime movers in an island mode operated FPSO power system network when the combined cycle power plant is selected? That was the main question to be solved in this design. Consequently, the load flow, short-circuit currents and motor starting conventional studies need to comprise some operating conditions to include the combined cycle power plant.

Usually for the load flow studies, two conditions were considered: (1) the normal operation and (2) the secondary selective "*L*" operation to evaluate the losses and voltage levels at all switchgears and distribution panels. Specifically for the STG, the second condition need to be evaluated since there was a lower power capacity.

Considering short-circuit currents, the condition (2) above defined the maximum values for short-circuit. However, it was necessary a complementary study to allocate the STG on another busbar – thus increasing the unit complexity with the introduction of one more pyrotechnical limiting device - or in the same busbar with the other GTGs.

For the starting of the larger motors and defining the voltage drop at the most impacted panels, the design constraints were eased by using medium-voltage VSD's. Without that, to successfully start such motors, it would require at least two GTG in service with field forcing enabled. In this case, when starting the FPSO unit (Black Start), the STG would be out of service, and it shall not be considered as an available power source for starting motors.

B. STG CAPACITY

The main challenge to properly operate a FPSO power system network with a single STG based combined cycle power plant is to keep track of the available STG load capacity at a given time. This parameter is time variant and depends mainly on the total heat available from all GTG in service exhausted gases. But such heat is also required by the Waste Heat Recovery Unity (WHRU) that provides all required heat for the FPSO process plant. The remaining heat will be available for the STG operation. Therefore, the parameters that limit this generator power output are the number of GTG in operation, process plant heat demand, and, also, ambient temperature. Considering three 33.0 MW GTG's, all with WHRU, the STG output can vary from 20.0 MW to 28 MW. The dependency of the maximum available STG output power on so many variables will lead to a more complex PMS implementation, including more complex load sharing and load shedding strategies.

IV. VSD DRIVEN LOADS

There are pros and cons when using VSD's to drive and control electric motors. Considering GHG emissions, the use of VSD's has a direct impact in efficiency and power demand reduction when compared to valve flow restriction and hydraulic speed controller strategies. However, far from the total controlled VSD unit [6] the application of VSD in some offshore unit plant services has achieved gains discussed as follows.

A. COMPRESSORS

Typical solution for main compression system speed control in FPSO units is based on hydraulic speed controlled VSD (HVSD), due to its sturdiness. However, the need for GHG emission reduction led to an updated internal driver selection methodology, with new parameters being taken into consideration: efficiency and emissions.

The FPSO unit production is heavily depended on compression systems, so a failure in one of the main compressors leads to considerable production losses.

In addition to that, such compression systems are the FPSO unit largest loads. In recent studies, compressors ranged from 10 MW to 20 MW and were responsible for 50 % to 75 % of the total demand.

Based on internal data, for offshore application HVSD presents better reliability performance than power electronic based VSD. However, when data including CAPEX, OPEX, Structure requirements, oil production losses, efficiency, and emissions is considered, in some cases VSD's present lower levelized cost of electricity (LCOE). And when considering GHG emission reduction, including carbon pricing, VSD solutions present lowest LCOE results.

In some studies, system CO_2 emissions reduction per group of compression along the full FPSO unit lifetime can be around 0.5 % to 1.0 % [10][11][12]. These values were obtained in internal studies considering the VSD efficiency versus an hydraulic solution. The reduced kW was transformed in natural gas not used into the turbine, and thus calculated in CO_2 equivalent not emitted. These reduction values considered a 30-year operation.

When compared to HVSD, VSD can be more efficient, by saving 1.0 MW to 2.0 MW from the overall FPSO unit demand, and, statistically, motor lifetime performance is improved, since it provides better controlled starting.

B. WATER INJECTION PUMPS

The use of VSD's for water injection pumps allows well injection system pressure and flow variation [8]. When DOL motors are used, it is necessary to maintain the injection water head at the maximum pressure all the time. Therefore, the pressure control for each well is done typically by controlling a discharge valve and, consequently, the water flow. This control strategy leads to high maintenance cost and a less efficient system. When either VSD or HVSD are used, the maximum pressure for a specific well can be set only when necessary, leading to a more efficient, less failure prone and, therefore, more reliable system. For the present scenario, as can be seen in Figure 2, the VSD's were the best solution, since it was not only able to better manage the discharge pressure, but also able to reduce system demand. Such approach led to a demand reduction ranging from 4.0 MW to 8.0 MW.

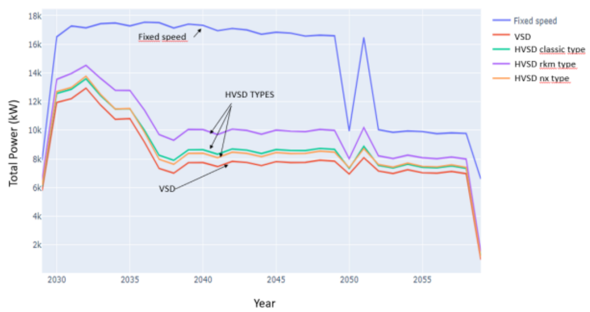

Figure 2: Load reduction study comparison.

C. VSDS IN SUBSEA APPLICATIONS

Since the FPSO unit under development is for an oil production field in operation for more than 30 years (brownfield), subsea artificial lift methods are necessary to increase oil production. The selected option was Subsea Multiphase Pumping Systems [13]. i.e., multiphase (gas and liquid) pumps operating at deep water seabed to improve oil and gas production.

Typically, the multiphase pump is driven by a three-phase 60 Hz medium-voltage submersible induction motor filled with a dielectric oil (barrier fluid) slightly overpressurized, i.e., at an inner pressure slightly greater than the outer (at seabed) pressure. Means are available to limit such positive pressure differential. In the present case, such sealing system requires a Hydraulic Power Unit (HPU) located at topside.

The required electric motor rated voltage can vary from 5.0 kV to over 11.0 kV and the rated power can reach values of 6.0 MW.

Because of the need for the VSD be located at topside, its output is connected to the submersible electric motor via a long medium voltage power cable, ranging from few kilometers to around 15.0 km.

The resultant increment in oil and/or gas production for brownfields can compensate the associated costs and the increment in area/weight requirements at the FPSO unit.

For the power system network, overall load demand and voltage and current harmonics are the main concerns. Usually, 36-pulse CHB drives are used. In the present study case, 4 drives suppling subsea loads where considered.

V. POWER SYSTEM HARMONICS

Since replacing all HVSD based loads with those driven by VSD's, it was necessary to evaluate the THD_V (*Voltage Total Harmonic Distortion*) at the FPSO power system network's main 13.8 kV busbar and to compare the results with the limits stipulated by [14] and [15] i.e., 5.0 % limit for THD_V and 3.0 % for each individual voltage harmonic.

For the present harmonic analysis, it was considered the following loads in service:

- 2 (two) main compression systems;
- 2 (two) water injection systems;
- 2 (two) export gas compression systems;
- 4 (four) subsea multiphase pumping systems;
- 1 (one) offshore ESP systems.

The purpose of the harmonic analysis is to identify the need for potential power system upgrades to comply with THD_V limits as per [14] and [15], which can include minimum VSD pulse requirements and the use of passive/active filters.

A. POWER SYSTEM TO BE EVALUATED

A preliminary voltage harmonic analysis was performed to estimate the THD_V at the FPSO power system main 13.8 kV switchgear.

Care was taken to include the required surge capacitors and surge arrestors to properly model all 13.8 kV electric motors and generators. The power cable capacitances were also included into the present analysis.

To optimize size and weight, it was decided to use 24 pulse VSD's for all applications, except for subsea multiphase pumping and ESP applications, which required 36 pulse VSD.

The power system that was evaluated is shown in Figure 1, with the following parameters:

Generators

Typical parameters values, as shown in TABLE 1, were used to model all gas turbines and steam turbine generators.

TABLE 1
ELECTRIC GENERATOR PARAMETERS

Tag[(2)]	GTG-001A/B/C/D	STG-002
U_{nom} [kV]	13.8	13.8
P_{nom} [MW]	33.0	31.0
Pf	0.80	0.80
X''_d [pu][(1)]	0.160	0.160
C_w [μF]	0.194	0.194
C_s [μF]	0.25	0.25
R_a [mΩ]	5.45	5.45

Note:

(1) For simulation purposes, an increase of 30 % in subtransient reactance was considered, according to tolerance defined in IEC 60034-1, "*Rotating electrical machines – Part 1: Rating and performance*". Therefore, for the simulation the value of 0.208 pu was selected.

(2) Parameters:
U_N: Nominal voltage;
P_N: nominal active power;
pf: power fator;
x''_d: direct axis subtransient reactance;
C_w: winding capacitance per phase;
C_S: surge supressor capacitance;
R_a: stator resistance.

Power Cables

The power cables comprised by all 13.8 kV feeders, with cross-section ranging from 70 mm² to 120 mm² were modelled, including resistance and both inductive and capacitive reactances. Typical values were used.

Electric Motors

All 13.8 kV DOL electric motors were modelled, including both surge and winding capacitances. See TABLE 2.

TABLE 2
13.8 KV ELECTRIC INDUCTION MOTORS

Tag	U_{nom} [kV]	P_{nom} [MW]	Winding Capacitance	Surge Capacitance
			C_w [μF]	C_s [μF]
M-001	13.8	1.80	0.05	0.25
M-002	13.8	1.80	0.05	0.25
M-003	13.8	3.15	0.0531	0.25
M-004	13.8	1.475	0.04	0.25

VSD's

All VSD's were modelled as a constant current source with all individual harmonics typical for its topology and demanding active power as required by the respective electric motor they are driving.

For each one of main and exportation compressors and water injection pumps, it was considered a 24-pulse VSD with current harmonic content as defined in TABLE 3.

For those VSD's that drive subsea loads, it was considered a 36-pulse VSD with current harmonic content as defined in TABLE 4.

TABLE 3
24-PULSE VSD CURRENT HARMONIC CONTENT

Harmonic Order	RMS [%]	Frequency [Hz]
1	100.00	60
5	0.04	300
7	0.03	420
11	0.01	660
13	0.01	780
17	0.01	1020
19	0.01	1140
21	1.21	1260
23	1.59	1380
25	1.61	1500
27	0.08	1620
29	0.02	1740
31	0.01	1860
35	0.02	2100
37	0.02	2220
43	0.01	2580
45	0.18	2700
47	0.67	2820
49	0.57	2940

B. SIMPLIFIED ANALYSIS

As a first step, a simplified methodology as described in [16] was performed. It states that the resonance frequency for a given power system topology can be estimated by the following equation:

$$h_r = \sqrt{\frac{MVA_{sc}}{MVA_{cap}}} \quad (1)$$

Where:

- MVA_{SC}: short-circuit apparent power at the FPSO power system network's main 13.8 kV busbar;
- MVA_{SC}: total capacitance apparent power as seen at the FPSO power system network's main 13.8 kV busbar.

TABLE 5 summarizes the results for different FPSO power system operating conditions.

C. EMT - ELECTRO MAGNECTIG TRANSIENT BASED ANALYSIS

The analysis was performed by using ATPDraw v5.9, with the equivalent circuit modelled as per Figure 1.

The first step is to evaluate the power system frequency response for frequencies up to the 50^{th} harmonic or 3.0 kHz for a 60 Hz power plant.

Using ATPDraw, the power system frequency response at the FPSO main 13.8 kV switchgear is estimated to be as shown in Figure 4.

TABLE 4
36-PULSE VSD CURRENT HARMONIC CONTENT

Harmonic Order	RMS [%]	Frequency [Hz]
1	100.00	60
3	1.69	180
5	0.94	300
7	0.30	420
9	0.19	540
11	0.23	660
13	0.08	780
15	0.09	900
17	0.19	1020
19	0.38	1140
21	0.19	1260
23	0.54	1380
25	0.51	1500
27	0.02	1620
29	0.09	1740
31	0.39	1860
33	0.12	1980
35	0.11	2100
37	0.06	2220

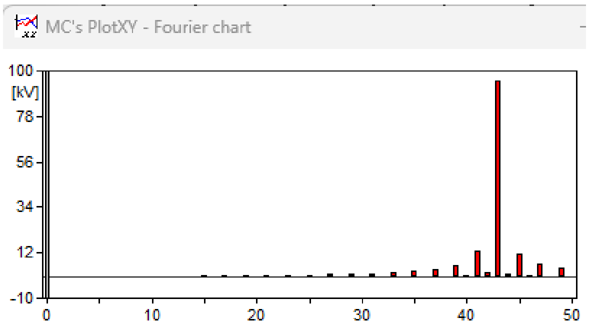

Figure 3: FPSO power system frequency response at main 13.8 kV switchgear.

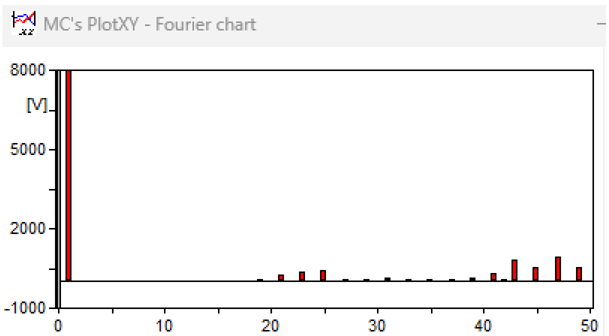

Figure 4: Voltage harmonic spectrum for Case #01.

TABLE 5
RESONANCE FREQUENCY FOR DIFFERENT FPSO POWER SYSTEM OPERATING CONDITIONS

Operating Condition	Resonance Harmonic	Observation
4 generators, double "*II*" configuration, Full Load	43^{rd}	3 gas turbines, 1 steam turbine generator and all power transformers in service.
4 generators, "*L*" configuration, Full Load	44^{th}	3 gas turbines, 1 steam turbine generator and only "*A*" tagged ending power transformers in service.
3 generators in service	41^{st}	3 gas turbines, double "*II*" switchgear configuration, only offloading and subsea loads out of service.
2 generators in service	40^{th}	Only one of each main compression, export and water injection systems in service. Subsea, offloading and VRU out of service.
1 generator in service	36^{th}	First main compressor start up. All 13.8 kV loads out of service but with power transformers energized.

It can be concluded that the FPSO power system has a resonance frequency around the 43^{rd} harmonic, corresponding to 2.58 kHz, at the main 13.8 kV switchgear.

CASE #01: Power System at full load, three gas turbine generators and one steam turbine generator in service

Figure 4 shows the voltage harmonic spectrum for the power system at full load with three gas turbine generators and one steam turbine generator in service.

For this condition, the estimated THD_V is equal to 19.0 %, exceeding the limits for total THD_V and for individual harmonic, as per [14] and [15]. This can be explained by the 24-pulse VSD having current harmonics (see TABLE 5) close to the power system resonance frequency (see Figure 4).

CASE #02: Single gas turbine generator in service, starting up the first main compressor.

Figure 5 shows the voltage harmonic spectrum for the power system with only one gas turbine generator in service and starting up the first main compressor.

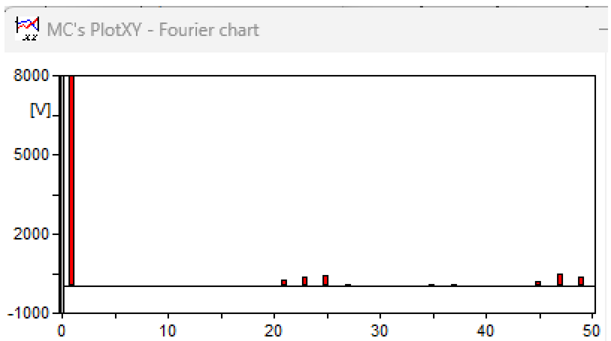

Figure 5: Voltage harmonic spectrum for Case #02.

For this condition, the estimated THD_V is equal to 9.9 %, exceeding the limits for total THD_V and for individual harmonic, as per [14] and [15].

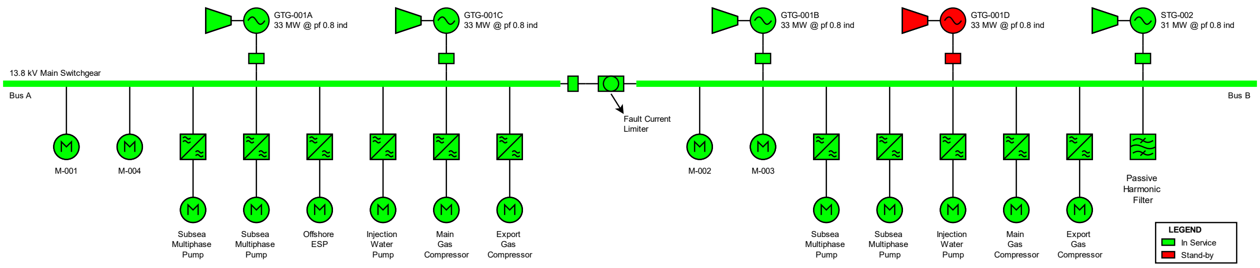

Figure 8: Simplified FPSO Unit Electrical Diagram with tuned passive harmonic filter.

CASE #03: Using a passive harmonic filter to improve *THD*$_V$ performance.

To improve *THD*$_V$ performance, Rakan El-Mahayni *et al* [16] propose the use of a tuned passive filter, an approach previously used in other FPSO units with VSD applications.

Therefore, it was decided to use a passive filter with the topology shown in Figure 6 and tuned at 1.44 kHz, corresponding to the 24th harmonic. TABLE 6 shows the filter parameters, calculated as prescribed in [16]. It is connected to the FPSO unit main 13.8 kV switchgear (see Figure 8).

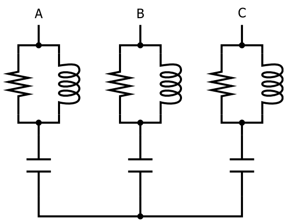

Figure 6: Three-phase tuned passive filter.

TABLE 6
PASSIVE FILTER PARAMETERS

Parameter	Resistance [Ω]	Inductance [mH]	Capacitance [μF]
Value	39.7	0.8778	13.93

With the power system at full load, three gas turbine generators and one steam turbine generator in service, the harmonic spectrum is as shown in Figure 7, with *THD*$_V$ equal to 4.33 % and every individual harmonic within the limits as per [14] and [15].

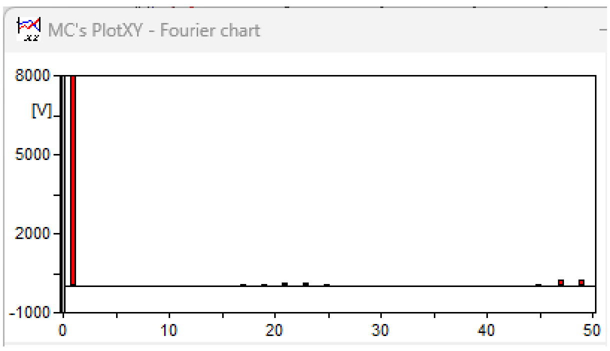

Figure 7: Voltage harmonic spectrum for the power system at full load, three gas turbine generators and one steam turbine generator in service and tuned passive filter connected at main 13.8 kV switchgear.

With the power system with a single gas turbine generator only in service starting up the first main compressor, the harmonic spectrum is as shown in Figure 9, with *THD*$_V$ equal to 0.95 % and every individual harmonic within the limits as per [14] and [15].

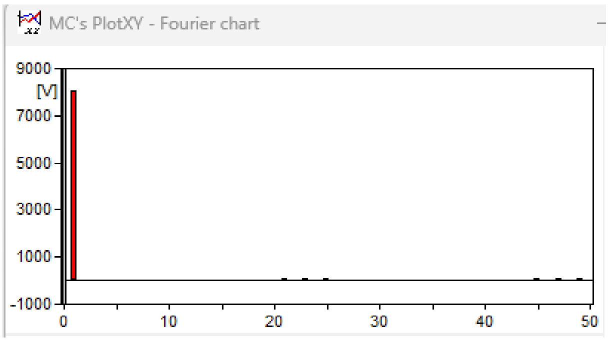

Figure 9: Voltage harmonic spectrum for the power system with a single gas turbine generator only in service starting up the first main compressor and tuned passive filter connected at main 13.8 kV switchgear.

Care shall be taken when tuning in and operating the passive filter. As can be inferred from equation (1), the resonance frequency can vary proportional to the square root of the ratio between short-circuit apparent power at the FPSO power system network's main 13.8 kV busbar and the total capacitance apparent power as seen at this same busbar.

Therefore, during detailing design phase, the impact of fluctuations in resonance frequency, due to the number of machines in service at a given moment and, consequently, the variation in short-circuit apparent power, shall be evaluated for the foreseeable scenarios.

It shall be kept in mind that more in depth studies are required, like evaluating power system network performance under phase-to-ground short-circuit fault, due to zero sequence capacitive current flows, but during the conceptual phase design it can be challenging to perform such studies due to lack of detailed enough information.

D. HARMONIC RESULTS AND THD MITIGATION OPTIONS

The present harmonic analysis indicates the need for harmonic filter to decrease *THD*$_V$ to values lower than the limits stipulated [14] and [15].

Such filter shall be specified taking into consideration not only the expected harmonic content from the selected VSD models to be installed in the FPSO, but also power cables capacitances, electric motors, and surge suppressors.

Regarding the harmonic filter, options are passive or active filters, but it can also include 13.8 kV active front end drivers. The decision may be decided based on size and/or weight restrictions.

VI. REDUCING GHG EMISSIONS

The efforts to reduce GHG emissions originated from a deep water FPSO unit to achieve the company goals and environmental agreements require multiple approach. Some short-term solutions can include the use of combined cycle power plant and the use of VSD driving the largest loads like compression systems, water injection pumps and subsea equipment. Production gains are also achieved: better control conditions, longer MTBF for motors, reduced generation power demand. Weight and volume increase is a price to pay for the desired benefits.

The use of combined cycle power plant alone has the potential to reduce from 15% to 20% of the GHG emission. Each compressor system converted to be VSD driven has a capacity to reduce from 0.5 % to 1 % of the GHG emission. Note that, for both opportunities values depend on the power and number of units considered.

Considering the indicated study case, the use of combined cycle and the use of VSDs has a GHG reduction margin from 16 % to 25 %, an average reduction of slightly over 122,000 ton_{CO2e}/year.

VII. CONCLUSIONS

The principal achievement in using combined cycle power plant and VSD driven motor in an offshore FPSO is the GHG emission reduction. Other consequences are the implementation of more efficient power systems. On the other hand, these solutions require increased weight and larger footprint, with a more complex system to run.

And a more complex system to run requires more complex studies to be evaluated during design phase. The evaluation of passive filter interaction with the FPSO's power system network across relevant operational scenarios requires not only steady-state but also transient analysis.

VIII. FUTURE WORK

Since the power demand of the FPSO is relatively high, further work will be conducted to validate the proposed linear busbar topology regarding operational steady state current values as presented in [2].

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