MV Multi-functional Retrofit Converter for Enhanced Power Quality on O&G Platforms

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***Abstract*—Retrofit solutions have been proposed and tested on Oil and Gas (O&G) platforms to ensure modernization and efficiency improvement, and to extend the lifetime of aging platforms. In this regard, many O&G rigs, both offshore and onshore, had to employ combinations of old DC motor drives and modern AC drives assigned to critical tasks. Taking advantage of the non-simultaneous load cycles on the target O&G platform, this paper proposes a medium voltage multi-functional retrofit Three Level Neutral point clamped (NPC) converter to enhance the power quality, not only of the connected load, but also at the point of common coupling (PCC), retiring the tuned passive filters, and reducing the burden of voltage regulation on On-load tap changing transformer. The selected system is modeled in MATLAB/SIMULINK and the results with the proposed retrofit are presented in detail, while comparing with the baseline system.**

***Index Terms*—Retrofit, multi-functional, NPC, power quality, oil and gas, active front end, STATCOM, active filter.**

I. Introduction

Moving towards decarbonization in O&G industry, both onshore and offshore, is challenging due to the particular characteristics of such installations. Various concepts have been proposed to adapt to the new environmental restrictions such as including energy storage systems, hybrid power plants with DC power supply [1], [2] and integrating renewable energy. Different approaches have been proposed for the technical and/or economic sizing of energy storage [3]–[5] for offshore O&G installations that integrate wind power. However besides those concepts, achieving the environmental goals is also associated with the efficient use of the existing equipment and its impact on the platform's power quality (PQ), which is seldom addressed.

Poor power quality is considered as an important factor threatening the safe and efficient operation of O&G platforms [6], [7] especially when several converter-interfaced sensitive loads are used [8]. This criticality is enhanced by the afore-mentioned trends of integrating converter interfaced devices, and may further contribute to harmonics interactions. In such weak grids, disturbances' propagation (i.e., harmonic currents from VFDs) can harm sensitive loads and for that bulky passive filters are required. Alternatively, active power filtering technologies have been proposed [9], [10] as a way to provide compensation in a flexible and compact way, however at the cost of increasing the total system complexity. Additional considerations for such type of equipment can arise due the footprint and weight restrictions on the O&G installations [11], especially for offshore systems. This highlights the importance of compactness and need for multi-purpose equipment. Another potential solution towards this direction is the implementation of smart retrofit solutions and the use of multifunctional converters [10], [12]–[15]. In this way, already existing converters can be used in a smart way to serve both as active front ends and active filters, supporting the local grid. Nevertheless, when such solutions have been proposed, they have mostly focused on low voltage (LV) microgrid applications and strong grids. In [16] a multifunctional converter was proposed to enhance the capabilities of the energy storage converter for an O&G platform but still focusing on the LV side and requiring the storage converter. Considering the above, in this paper an alternative retrofit solution targeting a Medium Voltage (MV) isolated O&G grid is proposed. A tailor-made 3 level NPC converter is proposed for retrofitting, capable of satisfying the local load requirements and providing additional power quality improvement to the PCC such as reactive power support and harmonic compensation.The case of a simplified version of an existing O&G installation [16] was considered to demonstrate the proposed solution while standardized industrial control procedures were employed, facilitating the applicability of the proposed concept in real-world conditions.

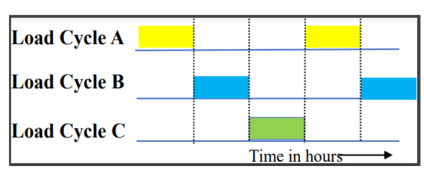
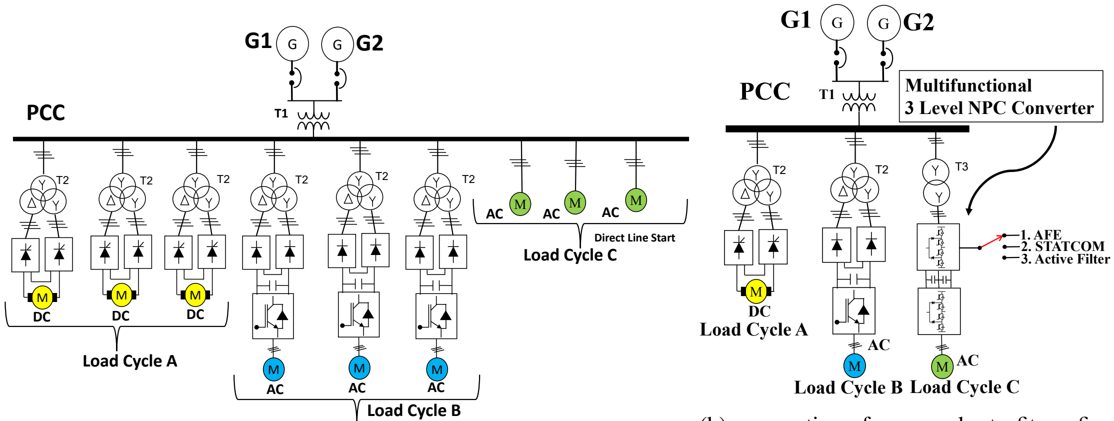


Fig. 1: Load Cycles



(a) Baseline power system under consideration

(b) one section of proposed retrofit configuration

Fig. 2: Baseline and proposed power system configuration

TABLE I: Power System Parameters

Component	Nominal Rating/Specifications
Turbine generators *G1*, *G2*	11 kV, 25 MVA, 60 Hz, X_d = 24%
Transformer - *T1*	11/6 kV, 25 MVA, X_{T1}= 4%
Transformer - *T2*	6/3/3 kV, 2 MVA, X_{T2}= 3%
Transformer - *T3*	6/3 kV, 2 MVA, X_{T3}= 3%
Motor - *DC*	8 kV, 2 MW
Motor - *AC*	3 kV, 2 MW, 0.9 Full load PF
3L Converter - C1	V_{dc} = 6.5 kV,2 MVA, C_{dc} = 30mF
3L Converter - C1	L_f = 1 mH, f_{sw} = 2.5kHz
Grid parameters at PCC	Short Circuit MVA = 157 MVA
Grid parameters at PCC	*SCR* = 6.25, *X/R* = 10

II. Platform power system configuration

Fig. 2a shows schematic from the installed offshore O&G platform in the North Sea, will be referred to as a baseline platform in the rest of the paper. This platform has two identical gas turbine-driven synchronous machines feeding the power distribution network at 11kV through the primary side of transformer T1. The secondary side of the transformer T1 is a 6 kV bus which is the point of common coupling (PCC) to all the motor loads. There are three types of motor loads on the considered platform, whose load cycles are named Load Cycle A, B and C. Load Cycle A is driven by three identical DC motor drives connected to PCC through 12 pulse thyristor rectifiers fed by three winding transformers T2 (star-primary, star and delta secondary). This arrangement is very common in medium voltage power distribution compared to conventional 6 pulse rectification, to eliminate at least the lower order 5^{th}&7^{th} harmonics. Load Cycle B is driven by three identical asynchronous motors driven by modern IGBT based variable frequency drives (VFDs) whose DC link is fed through 12 pulse uncontrolled diode bridge rectifiers connected to PCC through transformers T2. Load Cycle C has three asynchronous motors which are operated with a direct line connection to PCC and these are the identified loads that need retrofitting. The occurrence of the load cycles A, B and C is shown in Fig.1. For simplicity, and without compromising the validity of the approach, in the analysis, the time duration of all the load cycles is considered in seconds for simulation, whereas the actual operation could last hours or days. Hence, a feasible retrofit solution to improve PQ will be very beneficial. Planned retrofit aims to replace all three direct line connected Load Cycle C motors. Fig. 2b shows one section of the proposed retrofitted configuration where only one motor from each Load Cycle is shown. In other words, each retrofitted motor drive has a responsibility to improve the power quality of its own load and of two motor drives from Load Cycle A and B. All the nameplate details of electrical components are tabulated in Table I.

III. Proposed retrofit of multi functional converter

A. Need for retrofit

The existing platform suffers from huge inrush current with starting of direct line connected motors (Load cycle C) through contactors. There is also significant reactive power requirement from thyristor rectifiers and direct line motors during starting and at light loads. Adding to this, 12 pulse rectifiers (both SCR fed, and diode fed) add harmonics into the power system, which degrade the power quality at PCC and thus require bulky passive filters. Typically, passive filters are tuned to absorb dominant 11^{th}&13^{th} harmonics and often pose detuning challenges with aging, and unnecessary increase in PCC voltage when the connected load is significantly below the nominal.

To tackle these issues and taking advantage of the non-simultaneous load cycles on the target O&G platform, a Three-Level multi-functional active front end converter is proposed to retrofit load cycle C motors. Multi-level Neutral Point Clamped (NPC) converters are the preferred topologies for their high engineering readiness levels, reliability, and their wide acceptance in medium voltage drive industry. Their utilization can migrate low voltage systems ($\leq$1 kV) to medium voltage offering high power density electrification, specially on O&G platforms, reaping benefits through reduced cable

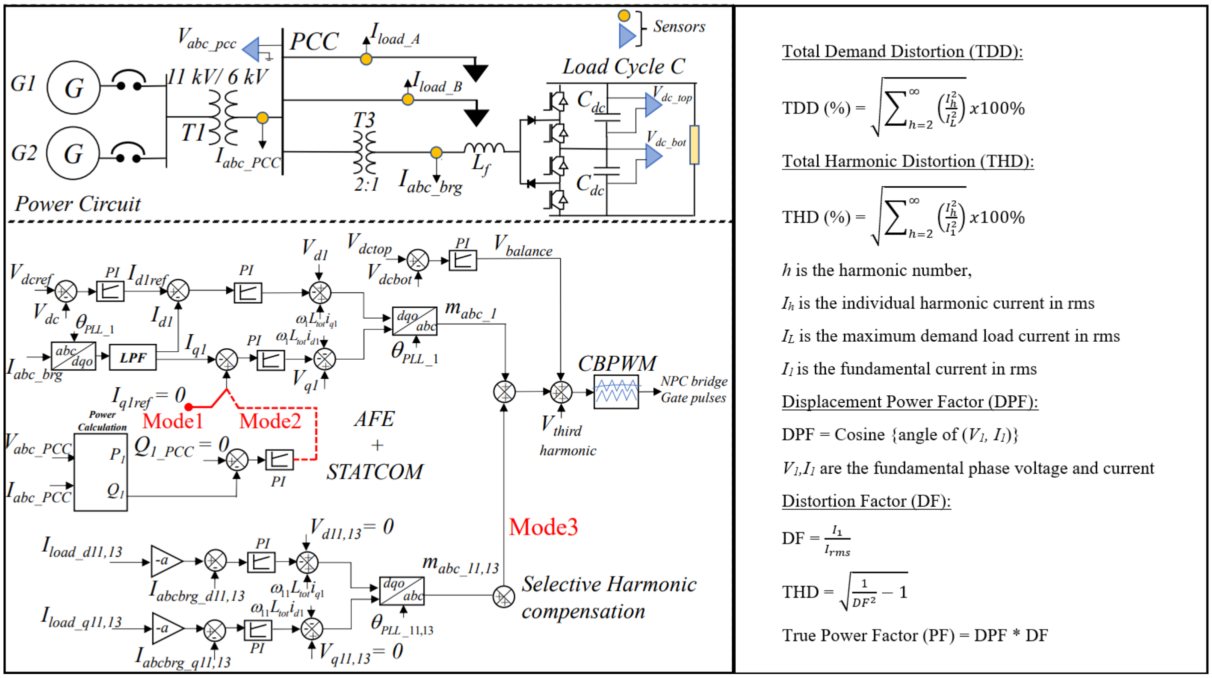


Fig. 3: Control Schematic of Multi-functional Converter

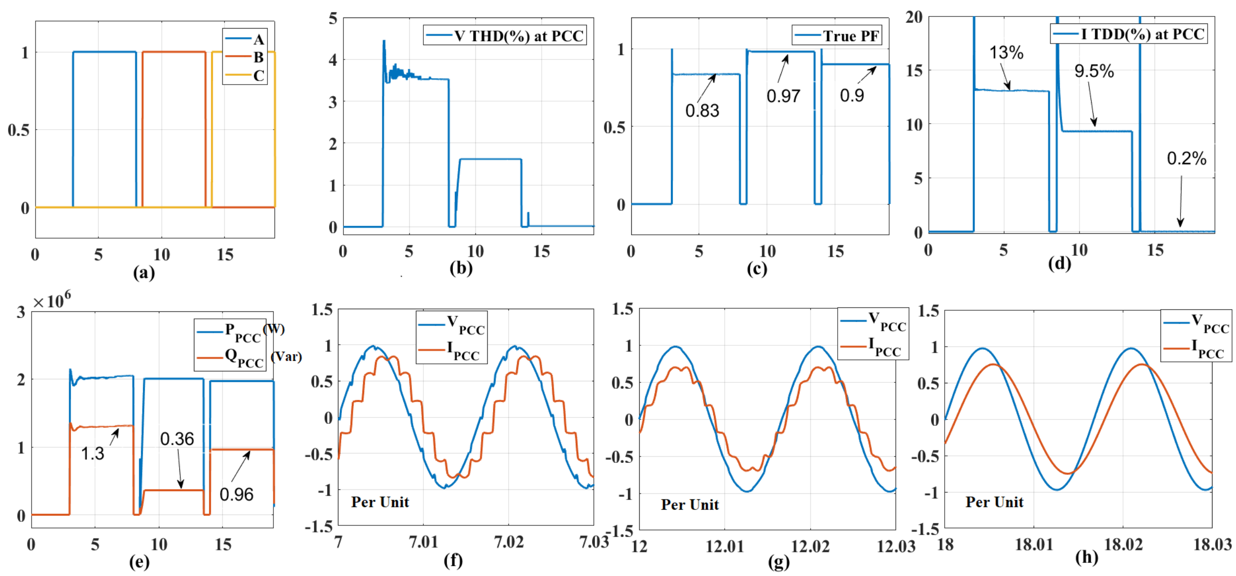


Fig. 4: Without retrofit (Baseline Case): a)Load Cycles, b)Voltage THD(%) at PCC,c)True PF at PCC, d)Current TDD(%) at PCC, e) P and Q at PCC, f-h) V and I at PCC for Load Cycle A,B and C respectively.

costs. The chosen retrofitting employs 3 Level NPC through 6 kV to 3 kV step down transformer T3 whose name plate details are also given in Table I.

B. Multi-functional 3 Level NPC

The power circuit, placement of sensors and the overall control scheme for the proposed 3 Level NPC converter is shown in Figure 3. The three multi-functionality services (Modes) are as follows. Mode 1: Active front end (AFE) converter for the self-connected motor drive having Load cycle C, ensuring improved power quality irrespective of the loading of the motor drive. Rotating reference frame based $dq0$ grid voltage-oriented control is employed in Mode 1. One DC link voltage proportional-integral (PI) regulator and two current PI regulators are employed to track fundamental active (d-axis) and reactive (q-axis) current references. Note that the reactive current reference is set to zero in this mode for unity power factor (UPF) rectification. The reference frame is synchronized to PCC fundamental voltage (60 Hz) with the help of phase-locked loop (PLL). The second mode of operation with this retrofit converter aims at reactive power compensation caused by the non-unity operation of Load A and Load B cycle drives. Instantaneous reactive power is calculated at PCC using p-q theory and fed as reference to be compensated in a STATCOM-like operation. This compensation requirement is mainly decided by the firing angle of the 12 pulse thyristor front end rectifiers of Load cycle A DC motor drives. As a STATCOM, the converter is expected to generate fundamental reactive (capacitive) current which uses the majority of the retrofitted converter capacity. Mode 3 implements active filtering, using synchronous reference frame (SRF) for selective harmonic compensation of $11^{th}\&13^{th}$ harmonics. Despite having many popular theories to control active filter, selective harmonic compensation is selected due to three reasons: 1) Offshore O&G platforms are often non grid tied (i.e not connected to shore) and are classical examples of weak grid systems – There exists a non-negligible impedance from the compensation point of the converter to the PCC, which demands higher converter terminal voltage as the compensated harmonic number increases. 2) Mode 3 will have to operate along with Mode 2 for both reactive and selective harmonic compensation sharing the available modulation index margin. 3) Since, switching frequency of the commercially available medium voltage 3 Level NPC at this power level varies between 2.5 kHz to 3 kHz (2.5 kHz is considered for worst case scenario), controller bandwidth is just sufficient to compensate 660 Hz (11^{th}) and 780 Hz (13^{th}) component. The resultant voltage references from all the modes are transformed into modulation commands and added with third harmonic for better dc bus utilization. Additionally, 3 level NPC converter requires neutral point balancing controller (PI regulator) to maintain equal voltages on top and bottom DC link capacitors. The output of balancing PI regulator is also added to the resultant modulation commands. Carrier based PWM (CB-PWM) technique is utilized to generate gating pulses for the converter. In the target system, 1 pu (2 MVA) rating of the retrofitted converter is sufficient to handle Mode 2 and 3(i.e. concurrently at the same time), as the most prioritized service from Mode 1 is occurring in different operational phases, i.e when load cycle A and B are off. Hence, only when the Load cycle C motor is turned off, the corresponding converter is idling and available, favoring the multi-functionality. This methodology for multi-functional converter operation can be extended to cases with a short overlap of the load cycles by placing a sufficiently oversized converter or additional converter in parallel.

IV. Simulation Results and discussion

A. Baseline platform - Power Quality

Fig. 4 shows simulation results of power quality key performance indicators for the baseline platform under consideration. Fig. 4a shows the occurrence of load cycles which are sequentially appearing without overlap. These load cycles could correspond to driving drilling, compressor, or water injection pump motors on the platform and hence they come with a scheduled sequence. Fig. 4b shows PCC voltage total harmonic distortion (THD) in percentage for all the three load cycles. The worse voltage distortion occurs during load cycle A, due to source voltage notches from 12 pulse thyristor rectifier commutation. True power factor (PF) i.e product of displacement power factor $COS(V_1, I_1)$ and distortion power factor is shown in Fig. 4c. At full load of each cycle, power factor of 0.83, 0.97 and 0.9 is seen for Load Cycle A, B and C, respectively. The low PF of 0.83 for load cycle A is due to the delay in fundamental current caused by the firing angle of thyristor rectifier. On the other hand, direct line fed motor at full load is drawing 0.9 PF load current, as given in its name plate reading. The 12 pulse uncontrolled diode rectifiers draw source current with approximately zero phase shift with respect to the source voltage, reflected into the 0.97 PF. Fig. 4d shows the total demand distortion (TDD) of the current in percentage for individual load cycles at PCC. Significant current TDD of 13% and 9.5% is seen for load cycle A and B, understandable from 12 pulse thyristor and diode rectification. As load cycle C motors are directly line fed without any power conversion, TDD of 0.2% is seen in the current. Fig. 4e, shows active and reactive power consumption for all the load cycles. The active power requirement in all the load cycles is around 2 MW whereas reactive power requirement of 1.3 Mvar, 0.36 Mvar and 0.96 Mvar is seen for Load Cycle A, B and C respectively. These values are in line with the true PF values seen in Fig. 4c. Fig. 4f-4h show simulation results of $V_{pcc}\&I_{pcc}$ in per unit for Load cycles A, B and C respectively before the retrofit.

B. Improved Power Quality with retrofit

Fig. 5 shows simulation results of control variables and power quality key performance indicators both during transients and steady state for the considered O&G platform with multi-functional NPC retrofit. The time sequence from 0 to 20 seconds is same as the time sequence shown in Fig. 4a. Fig. 5a shows the DC link balancing regulator performance during all load cycles. Top and bottom DC capacitor voltages $V_{dctop}\&V_{dcbot}$ are well regulated to half of the total reference DC link Voltage V_{dcref} which is 6500 V in this case. Fig. 5b shows PCC voltage total harmonic distortion (THD) in percentage for all the three load cycles. A slight increase in voltage THD (%) during load cycle C is now seen as compared to Fig. 4b, due to the presence of 3 Level NPC converter retrofit. True PF has been improved close to 0.96 for all the load cycles as seen in Fig. 5c. Fig. 5e shows the performance of the retrofit converter in Mode 2 (STATCOM). Active power of all the load cycles is around 2 MW whereas the reactive power drawn from PCC is zero inline to 0.96 True PF values in Fig. 5c for all the load cycles. Fig. 5f shows current TDD (%) at PCC. If compared to Fig. 4d (Baseline), current TDD (%) in Fig. 5f is improved from 13% to 6.2% for Load Cycle A, from 9.5% to 3.3% for Load Cycle B with just selective harmonic compensation of dominant $11^{th}\&13^{th}$ harmonics. An acceptable 3.2% of current TDD during load cycle C is seen, which is inevitable with active front end power conversion with a switching frequency of 2.5 kHz. Fig.

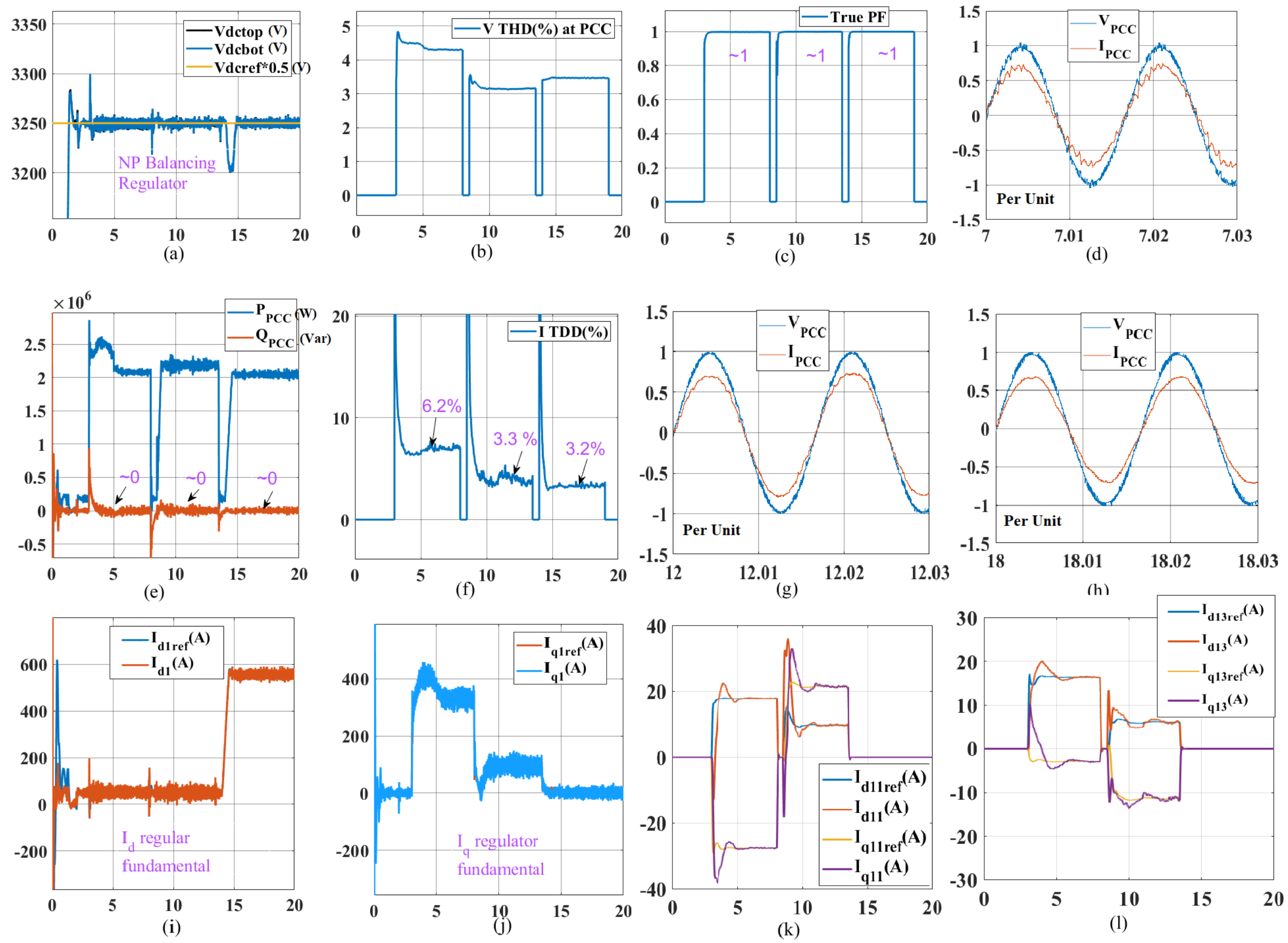


Fig. 5: With retrofit a)Neutral point balance regulator, b)Voltage THD(%) at PCC, c)True PF at PCC, d)V and I at PCC for Load Cycle A, e) P and Q at PCC, f)Current TDD(%) at PCC ,g-h)V and I at PCC for Load Cycle B and C respectively, i-j) dq axis regulators performance for fundamental, k-l) dq axis regulators performance for 11^{th} and 13^{th} harmonic.

TABLE II: Before and after Retrofit

Load Cycles	Reactive power at PCC (MVAR)		True PF= Displacement PF*Distortion factor		Current TDD (%)	
	Baseline	Retrofit	Baseline	Retrofit	Baseline	Retrofit
Load Cycle A	1.30	≈ 0	0.83	Unity PF	13.0	6.20
Load Cycle B	0.36	≈ 0	0.97	Unity PF	9.50	3.30
Load Cycle C	0.96	≈ 0	0.90	Unity PF	0.20	3.20

5d, Fig. 5g and Fig. 5h show simulation results of $V_{pcc}\&I_{pcc}$ in per unit for load cycle A, B and C, respectively after the retrofit. It can be clearly seen that the shape of the current is improved and in phase with the PCC voltage for all the three load cycles. Fig. 5i and Fig. 5j show the performance of the fundamental dqo current regulators. During load cycles A and B, fundamental active reference $d-axis$ is just drawing only losses from PCC, and it is tightly decoupled from fundamental reactive current loop $q-axis$ whose reference is proportional to instantaneous reactive power drawn from the loads. During load cycle C, only fundamental active power reference is seen as the retrofit converter is acting in active front end mode with UPF. Fig. 5k and Fig. 5l show excellent performance of 11^{th} and 13^{th} harmonic dqo regulators during dynamic conditions although weakly coupled due to non-negligible impedance in the system. The key power quality performance indicators before and after the retrofit are summarized in Table II.

C. Capacity utilisation of retrofit converter

The most important aspect of multi-functional converter is the dynamic availability of converter capacity for handling multiple services. For the considered retrofit, the analysis is extended to estimate the actual converter rating utilised for operating in Mode 3 (active filtering) alone and combination of Mode 2 (STATCOM) and Mode 3. In mode 1(active front end), it is obvious that the converter utilization is proportional to active power drawn by the load cycle C motor. Equation to compute utilized converter rating is as follows:

$$S_{utilizedpu} = (\sqrt{3} \times V_{bridge} \times I_{bridge}) \div S_{nominal} \qquad (1)$$

where V_{bridge}, I_{bridge} and $S_{nominal}$ are true rms line to line voltage, true rms line current and nominal rating of retrofit converter respectively. The true RMS computes the RMS of the total input signal(not just fundamental) over one cycle of the specified fundamental frequency. $S_{utilizedpu}$ is the utilised rating of the converter in per unit.

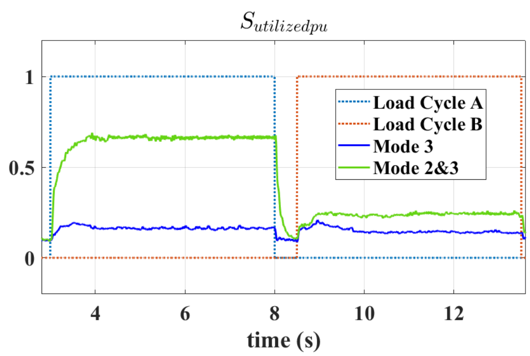


Fig. 6: Retrofit converter capacity utilisation

Fig. 6 shows the simulation result of computed $S_{utilizedpu}$ for Load cycle A and B when Mode 3 (alone) and combination of Mode 2 & 3 are enabled for the retrofit converter. This clearly validates two important findings. 1) For the chosen baseline platform, 1.0 pu retrofit converter is sufficient for the selected multi-functionality services for Load cycle A & B. 2) The converter utilisation as STATCOM requires higher capacity (maximum of 0.68 pu) than as active power filter (maximum of 0.2 pu). This is due to the STATCOM's ability to inject fundamental capacitive reactive current against the grid voltage.

V. Conclusions

A 3 level multi-functional NPC converter is proposed to improve power quality on a medium voltage Offshore O&G platform. The non simultaneous occurrence of loads has been taken as an advantage to propose the multi-functional operation without the necessity of over-sizing of the converter. The proposed retrofit multi-functional converter and its control for a typical medium voltage oil and gas platform power system help to achieve excellent results in reactive power compensation and harmonic elimination for the self-connected drive and the other polluting drives at PCC.

VI. Acknowledgment

This research is mainly funded under the program PETROMAKS2 of the Research Council of Norway, within the project "Smart Platform" (project number 308735).

Project / research funded by VISTA - a basic research program in collaboration between The Norwegian Academy of Science and Letters, and Equinor.

This scientific paper was supported by the Onassis Foundation - Scholarship ID: F ZP 056-1/2019-2020.

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