Application, Design and Optimization of Hybrid Filters for Oil Drilling Rigs

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***Abstract*— This paper presents the application of hybrid active power filters (HAPF) to mitigate harmonics problems in oil drilling rig system as a case study. In oil rig systems, where majority of the load is non-linear and varying over a wide range, the problems of harmonics are more severe and pose a challenge to the design of a filter which can work effectively at all loading conditions. Passive power filters (PPF) and active power filters (APF) are the main solutions used in the past to address harmonic problems. While the passive filters are not much suitable for varying system conditions, the active filters became popular because of their dynamic nature and high bandwidth operation. But APF still have drawbacks in terms of cost and reliability for its application in high power systems. Of late, HAPF which is a combination of both passive and active filters has gained much attention due to its potential advantages of cost and performance. The challenges in selecting a power filter for a rig system, optimal design of HAPF and its control strategy are presented are given in this paper. The performance is compared with conventional filters under variable load conditions. The simulation results show that HAPF has superior performance compared to conventional filters especially at light load conditions while reducing the overall cost of the system.**

I. INTRODUCTION

Increasing use of variable speed drives in industrial systems underscores the need for more effective methodologies to improve power quality. Improving power quality in industrial systems is of great importance as it yields in large amount of energy savings, increased equipment lifetime, reduced operational costs and improved economy. Harmonics generated by the variable speed drives are the main sources of power quality problems of a plant. Especially in oil rigs, where the majority volume of load is non-linear, the consequences of harmonics are more severe directly affecting the operational cost and efficiency. IEEE 519 harmonic standard [1] provides guidelines for maximum allowed harmonic pollution of plant on the basis of its short circuit ratio. To meet those stringent requirements, passive power filters (PPF) and active power filters (APF) are being used in the industry. These filters, referred to as conventional filters in this paper, were extensively studied in literature and a review of some topologies of these filters can be found in [2, 3]. Though the performance of these filters is satisfactory in some cases, there are still many limitations with respect to cost, rating, reliability and performance under variable load conditions. The challenging task is to design a power filter which can work seamlessly at all operating conditions of the plant from full load to light load. Passive filters have limited application in this regard as they can only be optimized for a fixed operating point. Also the ageing factors, variation in system frequency etc., will significantly deteriorate the performance of passive filters. APF resolves these problems but its application is still limited considering the cost and reliability especially when used in high power systems [4]. Also at light load condition the filter inductance (L_f) which is generally designed for full load, becomes small at light load that APF cannot track reference currents accurately. Hybrid active power filter (HAPF) topology on the other hand overcomes these limitations and provides a cost effective, high performance, and reliable solution.

The study system is an onshore oil rig consisting of medium voltage and high power DC motors driven by conventional thyristor bridge converters. Study of passive and active filters for an oil rig system is presented in [5] at full load and half load. The aim of this paper is to compare the performance of hybrid filters for an oil drilling rig with other conventional filters when the load is varying over a wide range. Section II summarizes the details of the system considered for this case study, section III presents design and in section IV particle swarm optimization is presented. Control strategy of hybrid filter is discussed in section V. Simulation results are given in section VI. Experimental setup for hybrid filter is under development, results for active filter system are only presented in section VII. Finally, the performance comparison of HAPF with conventional filters and conclusion remarks are given in section VIII.

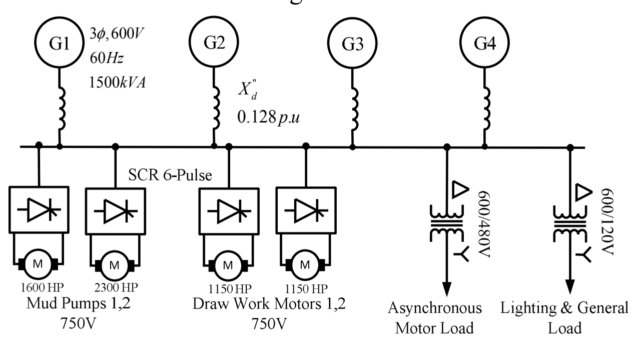

Fig.1: Schematic diagram of oil drilling rig with DC drives

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II. SYSTEM DETAILS AND FIELD DATA

The schematic diagram of a DC onshore oil rig is shown in fig. 1. A typical oil rig consists of consists of a pair of mud pumps (MP), a pair of draw work motors (DW), four synchronous generators with diesel engines as prime movers and transformers with linear loads. Ratings and details of the equipments are shown in fig. 1. The power supply of these oil rigs is independent and not connected to grid, hence can be treated as island systems. A typical rigging operation cycle spans about 3-4 weeks during which mud pumps used for circulating drilling fluid into the bores and draw work motors used for pulling the drill line will operate either simultaneously or separately, varying the load on generators. Synchronous generators are put online or offline according to the load demand. This consequently changes the effective source impedance and short circuit ratio. Harmonic currents caused by the non-linear load results in heating of generators and wires, increased losses, reduced efficiency and wear and tear of mechanical parts. Harmonic level at main bus varies as a function of loading on each drive, firing angle of converters and source impedance. Source impedance varies as the number of generators online is changed and thus the short circuit ration. Linear loads such as asynchronous motors, air conditioning and lighting consume about 20% of the total non-linear load and assumed to be present all the time.

To study the power quality problems and to develop simulation model, data is collected from three rigs working at full, medium and light loads. Current waveforms from CTs and voltages at main bus terminals are recorded using high bandwidth oscilloscope and total harmonic distortion (*THD*) readings are collected using power quality meter. Fig. 2 shows recorded voltage and current waveforms at rig 2 working at partial load (60%). Rig is working at medium load with DW and MP drives operating simultaneously and loaded partially. current *THD* (I_{THD}) recorded as 18.6%. Rig 1 is working at light load with only DW1 in operation. I_{THD} in this case is recorded as 19.4%. Rig 3 is working at full load with both DW and MP drives are fully loaded and I_{THD} recorded as 27%.

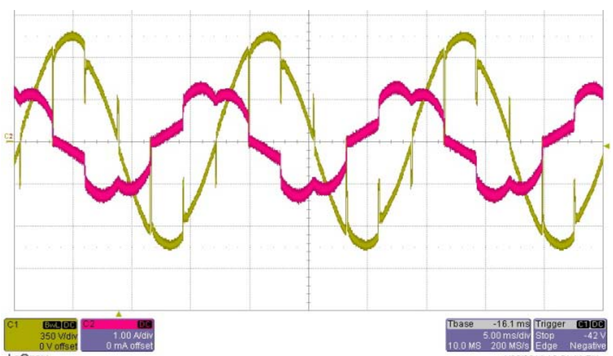

Fig. 2: Recorded voltage and current waveforms of rig working under partial load

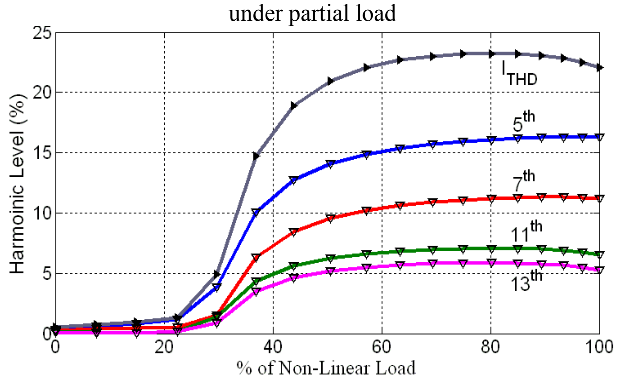

Fig.3: Harmonic variation with non-linear load

To study the variation of I_{THD} the system is simulated for different loading conditions. A constatnt linear load equal to 20% of full load is kept all the time in the simulations. The variation of 5th, 7th, 11th and 13th harmonic currents with load are shown in fig. 3. It is observed from the simulations that, *THD* is high when all the drives are triggered at same firing angle than at different angles for a given load. All the drives are triggered at same firing angle at each operating point to get worst case *THD* readings.

The design challenges of a harmonic power filter in this application are (i) the designed filter should perform well at all loading conditions of the rig as the load variations on the system are wide at every stage of a rigging cycle. (ii) The size of the filter should be small such that that it can be accommodated within the limited space available on the trailers that the rig currently have, and should not demand an additional trailer. (iii) Filter should be retrofitted or installed with minimum modifications in the current system like changes in bus bars, wiring etc. (iv) Filter should sustain harsh environment conditions of deserts. (v) Failure of the filter should not interrupt the drilling process for long as it may incur huge production losses.

III. HYBRID FILTER SELECTION AND DESIGN

There are many possible combinations to construct a hybrid filter using a passive filter and an active power filter. In [7, 8] systematic derivation of hybrid filter topologies are presented. They are mainly classified into two categories (i) parallel hybrid active power filters (PHAF) and (ii) series hybrid active power filters (SHAF). SHAF are used for voltage source harmonic type loads such as inverter fed drives whereas the PHAF topologies are suitable for current source harmonic type loads such as SCR drives [9]. Basic theory, analysis and modeling of hybrid filters are presented in [4, 6-8]. Although there are many variations in PHAF, the configuration shown in Fig.4 is considered in this study which is a series combination of APF and PPF. This configuration meets the design requirements stated in section II in terms of performance, size and reliability compared to other PHAF topologies. However, active filter is required to be protected from ambience unlike the passive filter, hence there is a compromise in selecting a filter sustainable environment conditions and its performance. Another shunt hybrid filter topology presented in [8], where APF is connected at the LC junction instead at end terminals, also meets the requirements. But this topology is not preferred in the present case due to its complexity in control.

Fig. 4 shows PHAF topology with APF connected to PCC through a double tuned LC filter. This configuration reduces the rating of APF by blocking fundamental line voltage to appear across the inverter terminals. Since APF controls the compensation current through the PPF, the system performance is independent of any deviation in passive filter tuning frequency that may seem inevitable due to manufacturing tolerances or ageing effects. The main steps involved in designing a hybrid filter are given below.

A. Selection of passive filter

The first step involved in designing a hybrid filer is to select passive filter size appropriately. The size of PPF affects the rating of APF. Passive filter shown in fig. 4 consists of two parallel connected single tuned LC filters. The relation between fundamental components of line voltage at PCC (V_{PCC1}), drop across passive filter (V_{f1}) and voltage at inverter terminals (V_{AF1}) can be expressed as in equation 1(a). It can be assumed that at fundamental frequency, V_{f1} is equal to drop across capacitor ($V_{c_{f1}}$) as the drop across inductor ($V_{L_{f1}}$) can be neglected. From the equation it can be inferred that if V_{f1} is equal to V_{PCC1}, inverter output voltage V_{AF1} can be zero. However, in order to oppose the line voltage, capacitor must carry some fundamental reactive current (I_{q1}) defined by equation 1(b), which in turn should be carried by APF.

$$V_{s1} = V_{L1} + V_{C1} + V_{AF1} \tag{1a}$$

$$I_{q1} = \frac{V_{f1}}{X_{C_f}} \tag{1b}$$

Smaller the size of capacitor is smaller the magnitude of I_{q1} and hence the rating of APF. But as per equation (2), for a given tuning frequency (ω_T), reduction in capacitor size must be compensated proportionately by increasing L_f. Large values of inductance limit the highest order of harmonic that can be compensated by APF. Hence inductance of passive filter should not exceed a limit L_{fmax}. This limits minimum capacitor size to C_{fmin}.

$$\omega_T = \frac{1}{\sqrt{L_f C_f}} \tag{2}$$

Furthermore, to have a reliable harmonic mitigation system the filter should have minimum reactive power rating (Q_{Cmin}). This value is selected such that in case of any failure of active filter, passive filter alone can provide reasonable level of compensation [10]. Following the relation given in equation (3), the maximum value of filter capacitor (C_{fmax}) can be expressed in terms of Q_{Cmin}.

$$Q_{Cmin} = \frac{V^2}{2\pi f C_{fmax}} \tag{3}$$

To avoid overcompensation, Q_C is limited to a maximum value Q_{Cmax}. In general the reactive power compensation limits of passive filter Q_{Cmax} and Q_{Cmin}, are chosen in between 20-25% of total kW rating of the system [2].

B. Optimization

From the above relationships it can be seen that the design of HAPF is a trade-off among the parameters Q_C, L_f and rating of APF (P_{AF}). The tuning frequency of the filter which reflects the current THD (I_{THD}), has to be selected without violating the above constraints. The objective is to minimize I_{THD} and P_{AF}. The objective functions and constrains are given in equation 4(a), 4(b). The two objective functions are combined into single function using weighting factor α_1 and α_2 as in 4(a). Particle swarm optimization (PSO) technique is used to solve these equations and is explained in the next section. The optimization problem can be summarized by the following equations.

Objective Function:

$$Min\ \{\alpha_1 I_{THD} + \alpha_2 P_{AF}\} \tag{4a}$$

Constraints:

$$(i)\ Q_{Cmin} < Q_C < Q_{Cmax} \tag{4b}$$

$$(ii)\ L_{fmin} < L_f < L_{fmax}$$

$$I_{THD} = \sum_{h=1}^{n} G_i I_{Lh} \tag{5}$$

$$G_i = \frac{I_{sh}}{I_{Lh}} = \frac{Z_f}{Z_{AF} + Z_f + Z_S} \tag{6}$$

Where, G_i is attenuation factor of h^{th} harmonic which is the ratio of h^{th} order source harmonic current (I_{sh}) to load harmonic current (I_{Lh}). Z_{AF} is the impedance representation of active filter which is explained in section V.

Prior to the optimization harmonic information is required to calculate the attenuation factors of harmonic currents entering the source. Optimal tuning frequency of the passive filter is calculated from these values. Even though the harmonic compensation capability of HAPF is independent of passive filter tuning frequency, an optimally tuned passive filter will ensure to minimize the size of APF. The optimum tuning frequency depends upon harmonic spectrum which varies with load. It is practically not possible to tune a filter for all operating points as the harmonic spectrum changes with operating point. For example, according to the harmonic pattern shown in fig. 3, the optimal tuning frequency at full load is 8.4th order and at 80% of non-linear load is 9.23rd order. The change is due to the increase in 11th and 13th harmonic currents with respect to fundamental. Hence the operating point should be chosen wisely to give maximum benefit in reducing the rating of APF.

The harmonic information at full load is stored as a look-up table. For every iteration the rating of active filter is calculated using equation (7).

$$P_{AF} = V_{AF} I_{AF} \tag{7}$$

Where V_{AF}, I_{AF} are the voltage and current ratings of APF given by the equation 8(a) & 8(b).

$$V_{AF} = \sum_{h=1}^{n} Z_{fh} I_{Lh} \tag{8a}$$

$$I_{AF} = I_{Lh} + I_{q1} \tag{8b}$$

Where, Z_{fh} is the impedance offered by passive filter to load current of h^{th} order (I_{Lh}). To get the harmonic information the system is modeled and simulated in MATLAB/Simulink, and the harmonic currents up to 50th harmonic are used in optimization.

Optimization is done for the cases with passive filter with a single tuned LC branch and two single tuned LC branches connected in parallel. The solution obtained for the single tuned filter case is 8.4th order harmonic. This result is in good agreement with the analytical explanation given in [14]. For the second case 6.7th and 12.9th orders were obtained as optimal tuning frequencies. α_1, α_2 are both set to 0.5.

C. V_{dc} Reference

V_{dc} reference should be selected such that APF can track reference compensation current. Since in ideal conditions, the LC branch blocks the fundamental voltage and will not appear at APF terminals, the only voltage to be generated by the APF is the harmonic voltage across the LC branch.

In pure APF, DC link voltage is controlled solely using direct component of current I_d. In hybrid filter DC bus is controlled using quadrature component of current I_q [11]. For accurate tracking of harmonic current V_{dc} reference should be at least 1.5 times that of voltage at active filter terminals V_{AF}. V_{AF} can be calculated from equation 8(a). A program is written in MATLAB to compute the voltage drop across Z_f by using pre-obtained harmonic information from the simulation.

D. Selection of C_{dc}

Capacitor value is calculated based on the energy to be transferred during transient conditions and the maximum voltage ripple allowed at steady state conditions. If ε is the maximum allowed percent of ripple in V_{dc}, then the minimum capacitor size is given by the equation (9)[12].

$$C_{dc} = \frac{I_{hpk}}{\varepsilon V_{dc} \omega_h} \tag{9}$$

Where, I_{hpk} is the highest order of harmonic current to be compensated and ω_h is the highest order harmonic frequency.

IV. PARTICLE SWARM OPTIMIZATION

PSO technique is a stochastic optimization method developed based on behavior of individual particles in a swarm. Swarm in this context refers to a random set of solutions to the objective function within a boundary defined by the constraints and particles are the members of the swarm. Each particle is moved by a small distance using velocity vector based on previous experience of whether the particle was drifted away from or closer to the global maximum. PSO technique can be used to deal with complex optimization problems and has better convergence characteristics compared to other techniques [14].

In PSO method the optimization process starts with an initial solution space; generally a set of initial values or particles (x_0^i), and their initial random velocities (v_0^i). The objective function is evaluated for the initial positions in the swarm and optimum particle position P_0^i is obtained. For the next iteration the particles are moved in random directions using velocity vectors according to the following equations [14].

$$x_{k+1}^i = x_k^i + v_{k+1}^i \Delta t \tag{10}$$

$$v_{k+1}^i = w v_k^i + c_1 r_1 \frac{\left(P_k^i - x_k^i\right)}{\Delta t} + c_2 r_2 \frac{\left(P_k^i - x_k^i\right)}{\Delta t} \tag{11}$$

Where, v_k is the velocity vector, r_1 and r_2 are random numbers in the range of 0 to 1; w is the weight factor; P_k^i is local best particle in k^{th} iteration, and P_k^g is the global best position in swarm up to k^{th} iteration. C_1 & C_2 are called 'trust' parameters indicating how much confidence the current particle has in itself (C_1) and how much confidence the particle has in the swarm (C_2).

In each iteration, the best position is identified in the swarm, compared with global best particle and, the entire swarm is moved toward the global optimum using updated velocity vectors. It is important that the initial vectors are randomly distributed around the entire design space to ensure global optimum is obtained.

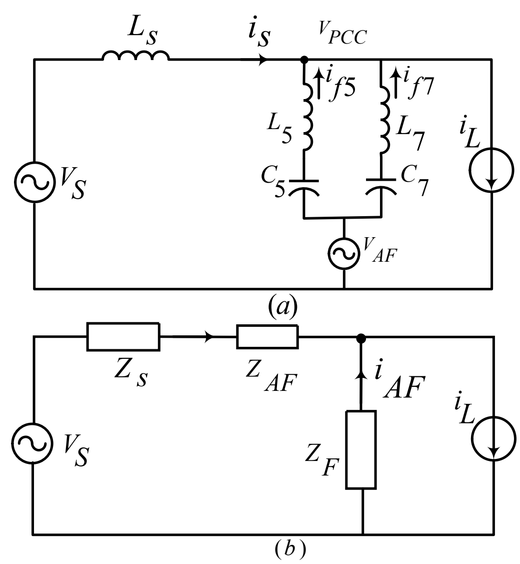

Fig. 5: Equivalent circuits (a) Single phase model of hybrid filter (b) Equivalent impedance representation of hybrid filter

V. CONTROL STRATEGY

Equivalent circuit of shunt hybrid filter is shown in fig. 5(a). The load can be represented as a current source I_L, which constitute both fundamental (I_{L1}) and harmonic currents (I_{Lh}). V_{AF} should be such that filter injects harmonic part of load current I_{Lh} at PCC and relinquish the source from producing harmonic currents. The behavior of APF can be modeled as a damping impedance Z_{AF} as shown in fig. 6(b). If Z_{AF} is high enough it can divert harmonic currents through Z_f. From the equivalent circuit, source to load harmonic current gain can be expressed as equation (12)

$$I_{sh} = \left|\frac{Z_f}{Z_{AF} + Z_f + Z_S}\right| I_{Lh} \qquad (12)$$

From above equation if Z_{AF} is very high I_{Sh}/I_{Lh} becomes small and source current (I_S) will be free from harmonics. But very high values of Z_{AF} can cause stability problems [14].

Fig. 6 shows the block diagram of control strategy. The line currents (I_L) are sensed and transformed to rotating dq reference frame of fundamental frequency. From the transformed currents I_{Ld} & I_{Lq}, the fundamental components I_{Ld1} & I_{LD2} are extracted. Low pass filter eliminates harmonic components from I_{Ld} & I_{Lq}, then they are transformed back to abc reference frame to get three phase fundamental components of line currents. To get harmonic component of current the fundamental component of currents are subtracted from line currents as shown in fig. 6. These are the reference currents to be compensated by APF. In addition to the harmonic currents, some fundamental component of current is required to control DC bus. DC bus voltage controller senses the voltage error and PI regulator processes the error to give the fundamental quadrature component of current (I_{q1}) to maintain increase or decrease DC link voltage. This current is added to the harmonic reference currents (I_{Lh}) as shown in the black diagram. The reference currents are tracked by a hysteresis current controller based on current error. The current is maintained within hysteresis band ($\pm\Delta i$) around the reference currents.

VI. SIMULATION RESULTS

Simulation is carried out in MATLAB/Simulink environment for DC oil rig system at different operating points from no-load to full load. Different filters are connected to the system one at a time and for every filter, the harmonic distortion with changing load is noted. The filters used in simulation are: pure passive filter with 5th, 7th and a high pass filter (cutoff frequency>13th), pure active filter, hybrid filter with non optimized passive filter and hybrid filter with optimized passive filter. In pure passive filter case the tuning frequencies are detuned by 5%. Filter parameters of optimized HAPF are summarized in table 1 along with other system parameters. The I_{THD} values obtained from the simulation for all the filters are shown in fig 7. It can be seen from the figure that the performance of HAPF is better compared to other filters and *THD* is within the limits. From the plot it appears that at light load condition the pure passive filter has better *THD* profile than other filters. This is because at light load

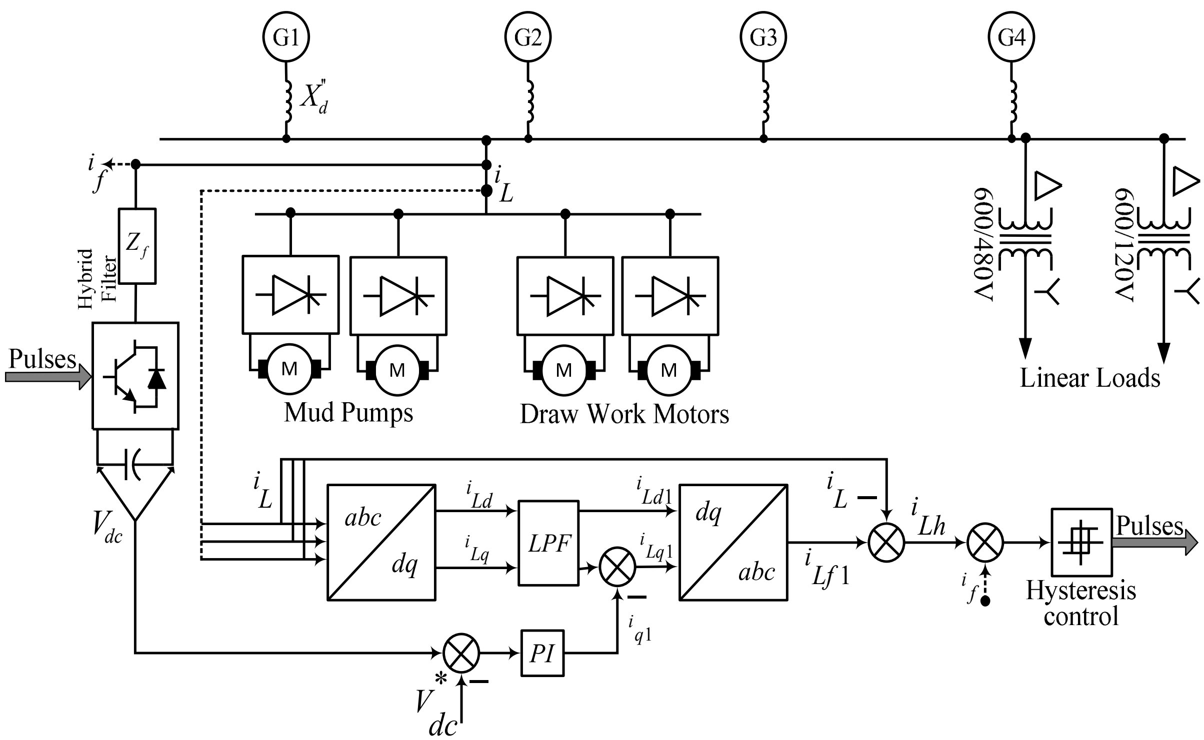

Fig. 6: Control block diagram

conditions the reactive current drawn by PPF is much higher than harmonic current. This sometimes has an adverse affect on the system due to over compensation. To avoid overcompensation passive filters should be installed in small units and some units should be switched off at light load. But this requires more space and mechanism to switch the filter banks.

Active power filter overcomes the problem of high reactive current at light loads. However, it still has a disadvantage that at light loads, tracking of reference current is not accurate. Since L_f is designed considering full load compensation current and maximum switching frequency (f_{sw}) which is much lower than the required value at no load. This causes high ripples I_f because of high di/dt. But in hybrid filter this problem is less severe because voltage across passive filter can be controlled using I_{q1}. From the equation (1) it can be recollected that the voltage drop across link filter V_f is sum of fundamental voltage (V_{f1}) and harmonic voltage (V_{fh}). Since current raise or fall in inductor is dependent on V_{Lf}, by changing I_{q1} it is possible to change $V_{L_{f1}}$ and reduce current steepness. This reduces current tracing error and improves harmonic compensation. The same is reflected in THD as can be seen in fig. 7.

Simulation results for full load condition are shown in fig. 9. DC link voltage is maintained at $400V$ as compared to $1300V$ in pure active filter case. It can be seen from the results that the reference compensation current is being tracked well even for low DC link voltage. Harmonic spectrum upto 50^{th} harmonic at full load is shown in fig. 8 along with PPF and APF at full load.

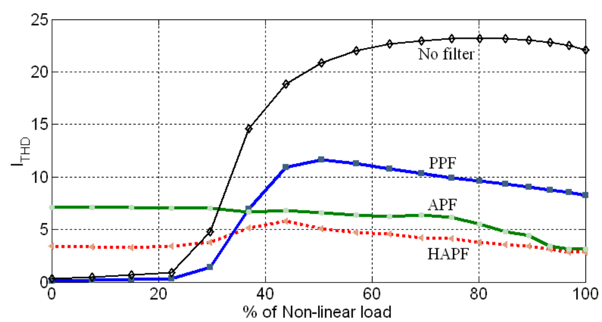

Fig.7: THD comparision of various fitlers

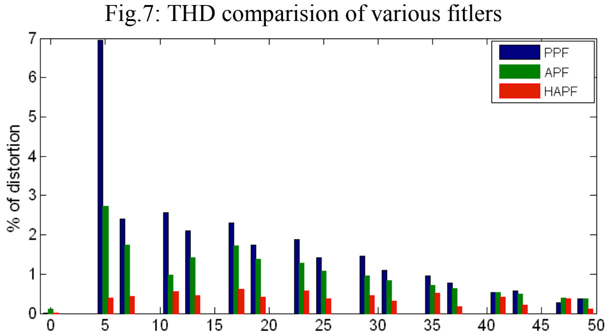

Fig. 8: Harmonic spectrum of PPF, APF and HAPF at full load

Table 1: System parameters used for simulation

L_s	$17\mu H$	C_1	$3.02mF$
V_s	$600V, 60Hz$	L_1	$55.4\mu H$
V_{dc}	$400V$	C_2	$3.5mF$
C_{dc}	$4700\mu F$	L_2	$7\mu H$

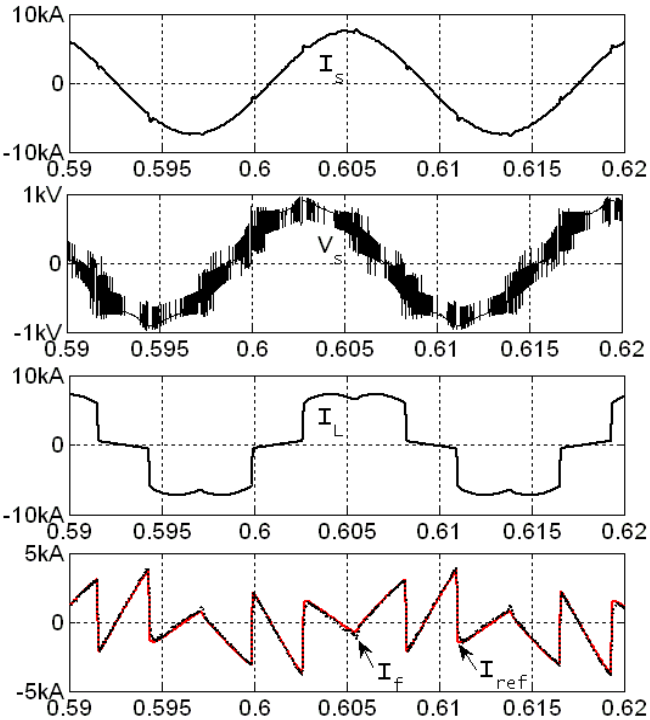

Fig. 9: Simulation Results at full load (a) I_s, (b) V_{PCC} (c) I_L (d) I_f overlapped on I_{ref}

VII. EXPERIMENTAL RESULTS

A prototype of the HAPF is under development. Experimental results have been taken for APF. The experimental setup consists of a diode bridge with RL load as non-linear load and inverter in series with link inductor. The results for APF compensating the load harmonics are shown in fig. 10. The parameters of the experimental system are given in table 2.

Table 2: Experimental system parameters

L_f	$5mH$
V_{dc}	$250V$
V_s	$150V, 50Hz$
Load	$1200W$

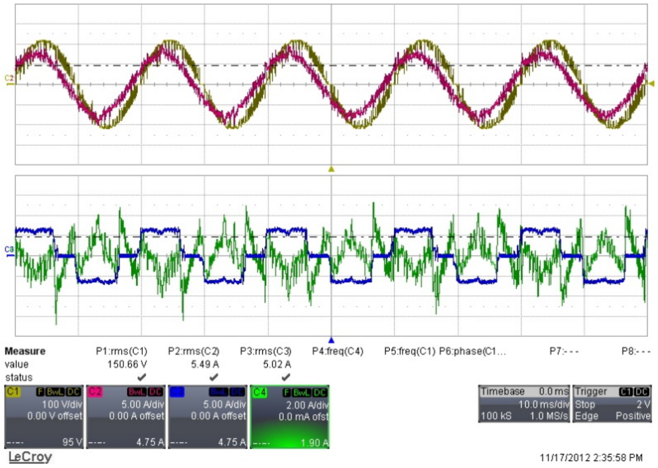

Fig. 10: Experimental results of APF. Trace C1:V_{PCC}, C2:I_S, C3:I_L and C4: I_{AF}

VIII. Conclusion

In this paper an overview of application of hybrid filters for an onshore oil rig consisting of DC motors is presented. Design equations, limitations and trade-offs in parameter selection are explained and optimization procedure is given to optimize the rating of HAPF. The ratings of different filters are summarized in table 3. The inverter rating of hybrid filter is reduced to about half the size that of a pure active filter. Simulations are carried out for all the loading conditions. I_{THD} is maintained within the prescribed limit at all the operating conditions. Experimental verification is under progress. Typical waveforms for an APF are given.

Table 3: Comparision of ratings of filters

Filter	Rating
Pure Passive Filter (5^{th}, 7^{th} & High pass >13th)	$1.2 MVAr$
Pure active power filter	$1.17 MVA$
Hybrid active power filter (LC branch tuned to 5^{th},7^{th})	APF-925kVA PPF-900$kVAr$
Hybrid Filter optimized (LC brach tuned to 6.7^{th},12.9^{th})	APF-590kVA PPF-900$kVAr$

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