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Study of Harmonic Minimization in Pulp and Paper Mill using Hybrid Active Filter -A Case Study

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Abstract: - Increased power electronics-based nonlinear loads have harmed distribution system power quality. Variable speed drives, switched-mode power supply, and DC drives impair power quality and affect customers and utilities. Many variable-speed drives in the paper mill cause harmonic distortion, a power quality issue. This study investigates the impact of nonlinear electric drives on supply current distortion in Padmavati Pulp and Paper Mill, Ambarnath, Thane, India. Harmonic analysis is done at PCC, that is, at the secondary side of the transformer, with the help of a power quality analyzer fluke-434. Based on detailed analysis, a suitable harmonic reduction method is identified. passive filters, are the simplest solution for lowering harmonic currents but it has shortcomings like bulk size and cause resonance. In recent years active filter has been applied as an effective solution for harmonic reduction. This study suggests a hybrid filter as an economical solution to take advantage of a passive and active harmonic filter. This work present design and simulation of cascade H- bridge multilevel inverter-based hybrid filter for medium and high-power distribution system. The system for the case study is developed in MATLAB Simulink platform with suitable harmonic mitigation techniques and performance is evaluated in terms of total Harmonic Distortion Index (THDi).

Keywords: Power quality, Harmonic distortion, Passive filter, Active power filter, Hybrid power filter Multilevel inverter, total Harmonic Distortion Index (THDi).

I. INTRODUCTION

In recent years, power electronics converters have been widely used in industrial applications. Variable frequency motors, renewable energy converters, and regulated rectifiers draw non-sinusoidal current from the supply, degrading power quality and system efficiency [1-2].

In the paper industry, many electric drives are used for production. This adjustable drive is a large source of current harmonics and causes power quality issues. This poor power quality supply causes an adverse effect on other components, like overheating of the transformer, failure of the capacitor bank, increase in energy consumption, and maloperation of relays. They also impact other consumers in the supplier network. Custom power devices with diverse configurations decrease power quality issues caused by nonlinear loads [3-4].

This study investigates the impact of harmonics due to electric drives used in the paper mill industry. The harmonic analysis is done with a Fluke-434 power quality analyzer. Based on the analysis carried out, a suitable solution is suggested to reduce the harmonics as per IEEE 519-1992 standards. This work presents the simulation analysis of the harmonic study of the Padmavati Pulp and Paper Mill industry. Simulation is carried out based on measured data and power quality analysis. The simulation is conducted to find the best solution for harmonic reduction as per IEEE standards.

There are many different approaches to reducing the harmonic pollution of nonlinear loads to meet the requirements of international harmonic standards [5-6]. Recently, hybrid power filters have gained a lot of attention because of their effective harmonic reduction [7].

This study uses real-time data from harmonic measurements to design and implement a hybrid power filter for harmonic reduction in MATLAB/Simulink. A double-passive filter lowers the low-order, high-amplitude 5th and 7th harmonics, while an active power filter reduces the remaining high-order harmonics. As a result, the active filter's rating and cost decreased. Additionally, since multilevel inverters generate output with fewer harmonics, reduced switching loss, and less switching stress, they are cost-effective alternatives in medium-power applications. Among the available configurations, this study uses the Cascade H-bridge 5-level inverter due to its modular structure, fewer components, and simple control method [8].

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II. HARMONIC ANALYSIS AND MEASUREMENT IN PADMAVATI PULP AND PAPER MILL:

Padmavati Pulp and Paper Mill is the second largest paper manufacturer in Maharashtra, with a production capacity of 15,000 MTPA. It has many AC and DC drivers for various processes. Electric drives power the dryer, reel, beater, and grinder processes that make pulp in the paper industry. The AC/DC motors can be driven singly or in groups. Continuously running drives use 65% of electricity. It has been found that converter-based electric drives create current harmonics. Current harmonics cause increased reactive power consumption, low power factor, and sensitive electronic component failure in electric drives.

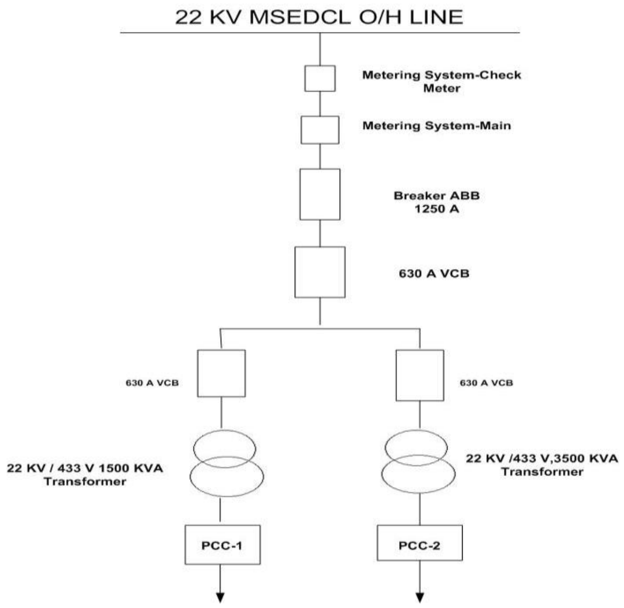

Figure. 1 single line diagram Padmavati Paper Mill

The electrical supply code and other conditions of supply -2005 by MSEDCL requires all HT and LT customers to control load harmonics per IEEE 519-1992. Therefore, a full power quality study is performed to determine harmonic distortion at the point of common coupling (PCC) and offer mitigation techniques. InstaSine Power Technologies Private Limited analysed power quality. The Fluke-434 analyses power quality metrics. It measured all three system voltages and currents. Power factor, THD, harmonic order magnitude, active power, and reactive power are monitored. The data analysis shows that motor drive harmonic content must be decreased to IEEE 519-1992 standards.

A single line diagram of the Padmavati Paper Mill's power supply system is shown in Fig. 1. Incoming line of 22 kV is feed to 1500 kVA and 3500 kVA ,22 kV/ 415 V transformers and power is drawn from 630 A vacuum C.B. The connected load is 5000 kW.

2.1 Power quality analysis at 3.5 MVA transformer

Figure 2 depicts a three-phase voltage and current waveform at the PCC, which is placed at the output of a 3.5 MVA transformer. To investigate power quality analysis 10-minute study has conducted at the transformer output. There is a noticeable deviation of three-phase voltage and current from their ideal sinusoidal waveforms. The loads taking current from this 3.5 MVA transformer have a current THD of around 26%, while the voltage THD shown in Figure 3 is about 10%. This transformer is displaying a harmonic current of 1170 A, and the plant current is dominated by the 5th, 7th, and 11th harmonics. Figure 4 shows the total amount of harmonic current generated by the plant equipment using the measured THDs of voltage and current. Table 1 displays the harmonic current summary.

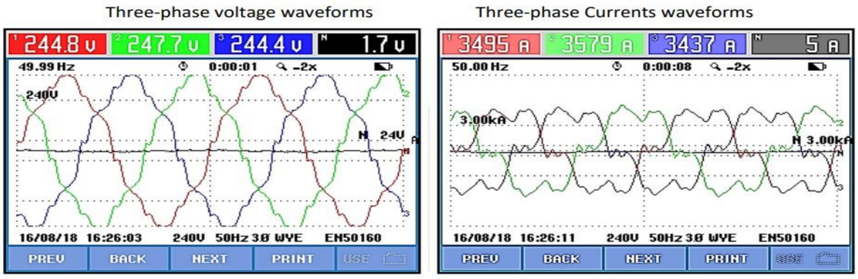

Figure 2. Three phase voltage and current waveform at the PCC-2

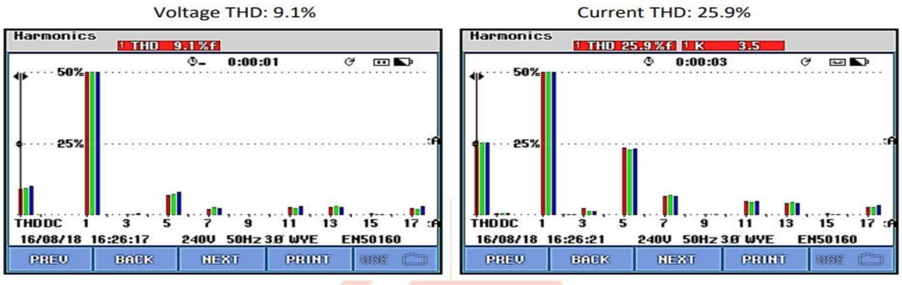

Figure 3. Volage and Current Total Harmonic Distortion at PCC-2

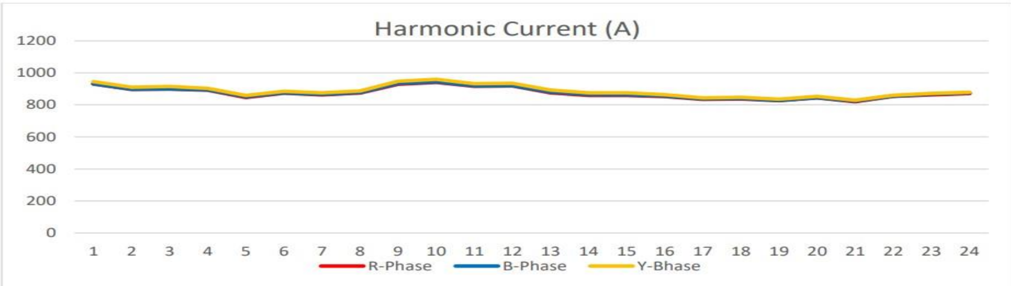

Figure 4. Total Harmonic current at PCC-2 for 24-Hrs

Table 1. 3.5 MVA transformer harmonic current Summary

Toal RMS Current (A)			**Current THD (%) [Harmonic RMS Current (A)**		
R-Phase	Y-Phase	B-Phase	R-Phase	Y-Phase	B-Phase
3505 A	3276 A	3210 A	26.64% [1151A]	25.93% [1172A]	26.21% [1154]

2.2 Power quality analysis at 1.5 MVA transformer:

The 1.5MVA transformer's load current THD is 23% and the voltage THD is 6% as shown in **fig.5**. A 350A harmonic current is drawn from this transformer, and 5th, 7th, and 11th harmonics dominate plant current. **Figure 6** shows the total harmonic current produced by plant equipment using observed voltage and current THDs. The harmonic current summary is in **Table 2.**

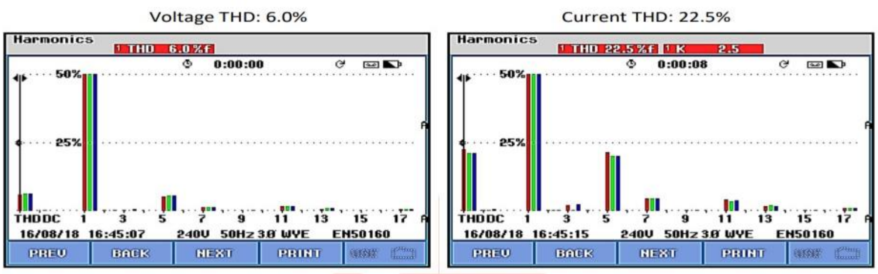

Figure.5. **Volage and Current Total Harmonic Distortion at PCC-1**

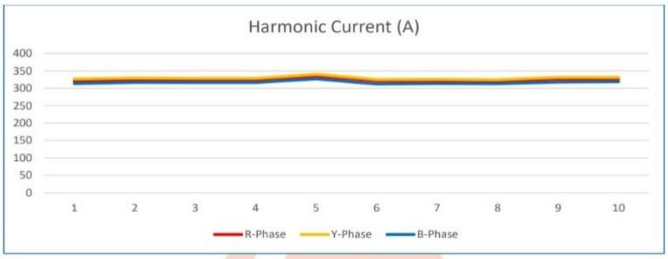

Figure.6. Total Harmonic current at PCC-1 for 24-Hrs

Table 2. 1.5 MVA transformer harmonic current Summary

Toal RMS Current (A)			**Current THD (%) [Harmonic RMS Current (A)]**		
R-Phase	Y-Phase	B-Phase	R-Phase	Y-Phase	B-Phase
3505 A	3276 A	3210 A	26.64% [1151A]	25.93% [1172A]	26.21% [1154]

III. HARMONIC REDUCTION USING HARMONIC FILTER

The power quality investigation reveals that the overall degree of harmonic distortion exceeds the IEEE Standard. Harmonics must be reduced to prevent negative impacts. Several compensation techniques, including hybrid, active, and passive filters, are investigated to lower these harmonics and it is observed that hybrid filter is the most effective solution.

This study simulates the system using MATLAB Simulink and measure the system's harmonic reduction without filter and with passive and hybrid filters. This study proposes a hybrid filter that combines passive and active filters to decrease harmonics. An active multilevel H-bridge inverter eliminates higher-order harmonics, while a passive double-tunnel filter suppresses dominant 5th and 7th harmonics. This lowers system cost and active filter rating.

Passive filters, or APF, are already deployed in many sectors these days in order to update the current system into a hybrid system. **Fig. 7** displays the control block diagram for the suggested hybrid filter.

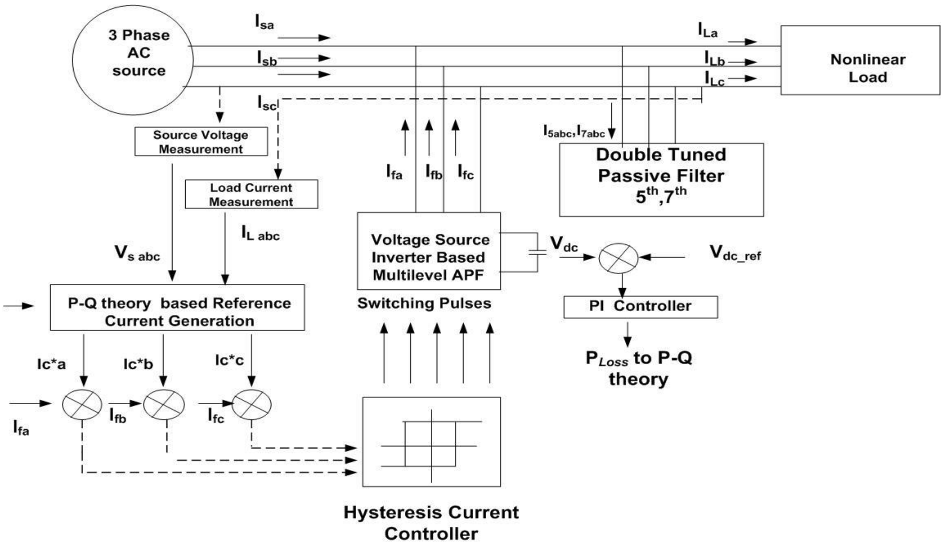

Figure.7 control block diagram of hybrid filter

The suggested hybrid filter connects passive and active filters in a shunt configuration at the PCC point. Reactive power of 5000 Var with quality factor (Q) 16 is considered in the design of the double-tuned passive filter components. A five-level multilevel H-bridge inverter is used in the design of the active power filter. A coupling inductor, a control system, and a voltage source inverter (VSI) with a DC-link capacitor (CDC) are all part of the active filter system. Active filter performance depends on control methods. It includes pulse production for active power filter voltage source inverter switching devices, DC link voltage management, and reference signal creation. The paper mill case study system was implemented using MATLAB/Simulink as follows.

3.1 Modelling of non-linear load as per test system.

The MATLAB simulation model of the system is shown in Fig. 8. The 3-phase source is connected to the non-linear load through the 11 kV/415 V transformer. The data gathered from the analysis is used to set the simulation parameters. Based on the test system's actual data, the nonlinear load is modelled to match the total harmonic distortion.

In MATLAB Simulink, an H-bridge inverter with a hysteresis current control loop (HCC) is used to model the non-linear load. With this, it is possible to obtain the source current harmonic spectrum as per the data obtained from the harmonic analysis survey. In this approach, a distorted waveform that has fundamental components and harmonic components that are integer multiple of the fundamental is given as a reference signal I_{ref} to the HCC loop. As per the working principle of HCC, the VSI will track the reference current, which is a distorted one, and will try to draw the same distorted current from the source and thus act as a nonlinear load.

The distorted reference signal (I_{ref}) is generated by adding the fundamental component (50 Hz) and sinusoidal frequency component, which are integer multiples of the fundamental component, and fed to HCC as shown in Fig. 9. To get the harmonic data as per measured data, the amplitude of the fundamental component and harmonic components are adjusted by masking the subsystem and creating a customized dialog box to assign values to the block parameter underneath of mask subsystem. The mask editor is used to create a customized dialog box. Having the same variable name as the customized mask dialog box and block parameter of the mask subsystem ensures that the mask editor parameter corresponds to the block parameter. By creating a customized mask dialog box, we can easily adjust the parameters of any block of a subsystem in the case of a complex system.

The mask dialogue box also allows to add buttons, sliders, and dials with a minimum to a maximum range of block properties. This customized dialog box is used to assign values to the block parameter of the underneath mask subsystem. Having the same variable name for the block parameter and mask editor parameter ensures that the edit parameter corresponds to the block parameters of various blocks of the subsystem.

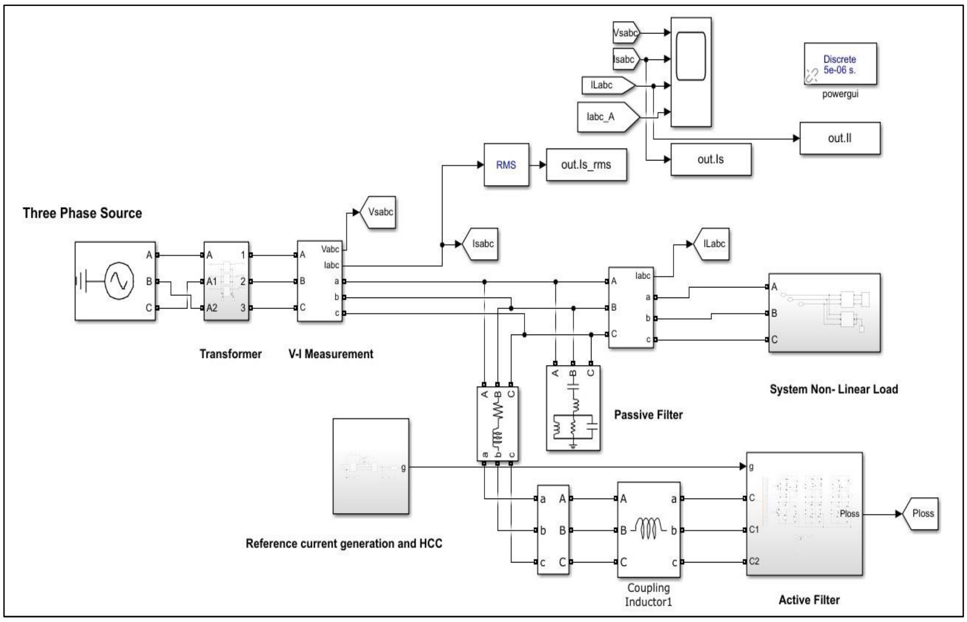

Figure. 8 Simulink model of system under study

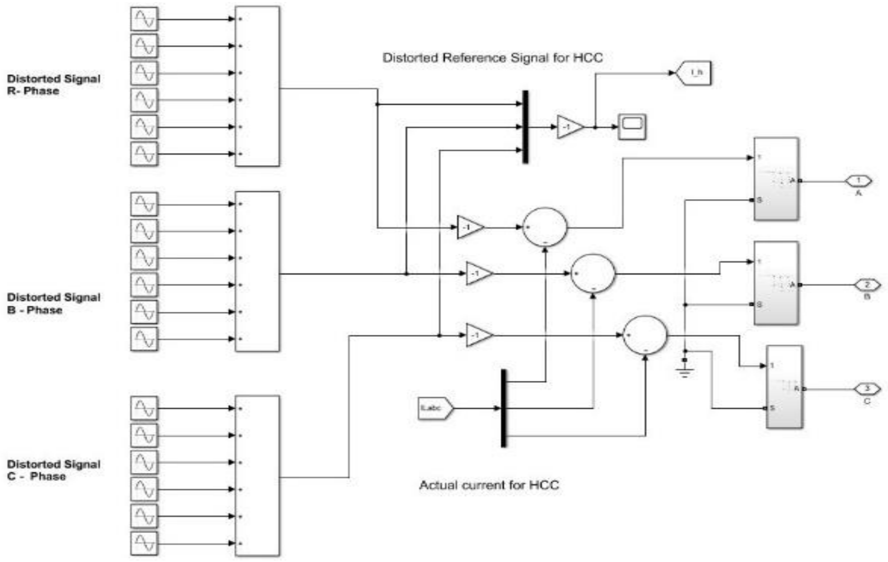

Figure. 9 Generation of distorted signal as reference to HCC to model nonlinear load of case study

According to test system data, the fundamental component amplitude is adjusted in the range of 0-5000 A, and the amplitude of the harmonic component is altered as per test data in Tables I and II using the customised mask editor dialogue box shown in Fig. 10. As per data in **table I, II** distorted signal is generated and given as reference to HCC. The VSI draws the current from the source by tracking reference signal which is distorted and acts as nonlinear load.

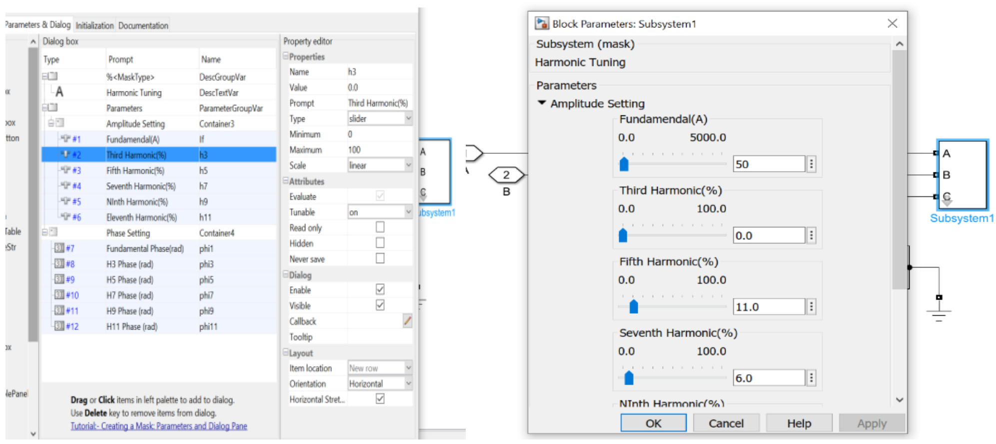

Figure 10 Customised mask editor dialogue box

3.2 Control of active power filter

This device generates equal and opposite harmonic current components at the point of common coupling to eliminate the load current's harmonic component and provide a sinusoidal supply. Figure 7 shows APF control installation procedures.

A. generation of reference signal:

The reference signal is generated by Akagi's instantaneous reactive power theory [9]. The key the basis involves using Clarke and inverse Clarke transformations to convert *abc* to α-β and vice versa. The computation of instantaneous reactive and active power comprises fundamental and harmonic components. The harmonic component is eliminated and used as a reference signal by a low-pass filter for compensation. The IPR theory produces reference current using these equations. Using Equation (1), the source voltage and load current are converted into α-β frames.

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \qquad (1)$$

The active and reactive power is calculated using equation (2)

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (2)$$

The active and reactive power have fundamental and harmonic components. The current in α-β frame is obtained using equation (3)

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \qquad (3)$$

Where $p = \tilde{p} + \bar{p}$, $q = \tilde{q} + \bar{q}$

The reference current is generated by using the oscillating components of real power ($\tilde{p}$) and reactive power (q) to compensate for harmonic power and reactive power. The loss component of real power p_{loss} is added to the harmonic real power component ($\tilde{p}$) of its reference value in order to correct for inverter switching losses and regulate DC link voltage to its reference $V_{DC\,ref}$Vdc ref value.

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} (p - \bar{p}) + p_{loss} \\ q \end{bmatrix} \qquad (7)$$

Finally, these reference currents are transformed to *abc* frame to get reference currents in *abc* coordinate.

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \qquad (8)$$

B. **DC link voltage control**: The regulation of the DC link voltage is necessary in order to mitigate the inverter switching losses. The PI controller is commonly employed in order to maintain the DC voltage at its designated reference value, $V_{DC\,ref}$. The PI controller receives the error between the reference voltage $V_{DC\,ref}$ and the actual voltage V_{DC} . A harmonic real power component is added to the PI controller output to generate the reference current generated by PQ theory($Ia^*\ Ib^*\ Ic^*$) [9-11]. This allows the reference current to contain information about the DC capacitor voltage Vdc. The error in DC voltage has been given as

$$e(V_{dc}) = V_{dc\,ref} - V_{dc} \qquad (9)$$

The error is passed through PI controller and output of PI controller is given by

$$H(s) = K_p\, e(s) + \frac{Ki}{s}\, e(s) \qquad (10)$$

Where Kp and Ki are proportional and integral gains and calculated using PID controller tuner

C. generation of switching signals for VSI: As shown in Fig. 11, a hysteresis current controller is used to provide the switching signal for the voltage source inverter. Upper band and lower band (+HB, -HB) are its two bands. In order to generate switching pulses for the inverter, it compares the actual filter current, If_{abc}Ifabc, with the current reference signal $I^*{}_{abc}$ of the APF. The error is then transferred through HCC to generate switching pulses for the inverter. The bottom group of the inverter switches ON when the error crosses upper HB (+HB), and the upper group switches ON when the error crosses lower HB (-HB), allowing the reference current to be followed by the actual filter current.

If er > + HB then Lower switches ON, Upper switches OFF

If er < -HB then Upper switches ON, Lower switches OFF

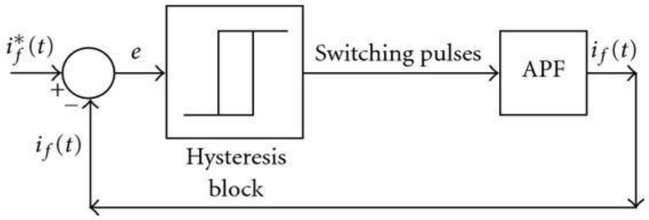

fig.11 Working block diagram of HCC

The active power filter in this investigation employs a 5-level H-bridge multilevel inverter. Hence, the current control technique is utilised to switch a 5-level multilevel inverter with multiband hysteresis. In the context of a conventional 2-level inverter, it is common practice to utilise two bands, namely upper and lower, for the purpose of HCC. However, as the n-level inverter has (n-1) hysteresis bands, the 5-level CHB inverter utilises four hysteresis bands for voltage levels of 2Vdc, Vdc, -2Vdc, and -Vdc. The switching frequency is determined by the breadth of the hysteresis band. The output voltage level of MLI depends upon the band crossed by the error[12].

IV. SIMULATION RESULT AND DISCUSSION.

To observe the compensating results of the constructed hybrid filter system, a simulation model of the suggested system is developed using the MATLAB Simulink platform. A step-down transformer is used to reduce the voltage of the 11 KV three-phase source to 440 V, which is then connected to a nonlinear load. The simulation parameters are presented in Table III.

Table III. Simulation Parameters

Parameters for simulation	**Values**
3 Ph. Supply Voltage	415 Volt ,50 Hz
Source Impedance	R=0.3 Ω, L=0.35 mH
Interfacing Inductor	R=5 Ω, L=0.3 mH
DC bus Voltage	750 V
DC link Capacitor (C_{dc})	2000 µf
Hysteresis Band	Upper bands + 0.02, +0.04 Lower band -0.02, -0.04
PI controller gain	Kp=1.5 Ki=0.2
Reactive Power	5000 Var

A. Simulation result without compensation.

Figure 12 depicts the waveform of the three-phase source current. The waveform exhibits distortion as a result of the existence of a nonlinear load. The harmonic analysis of the source current waveform, as shown in Figure 13, indicates a total harmonic distortion (THD) of 14.87%. The 5th and 7th harmonics are the most prominent harmonics.

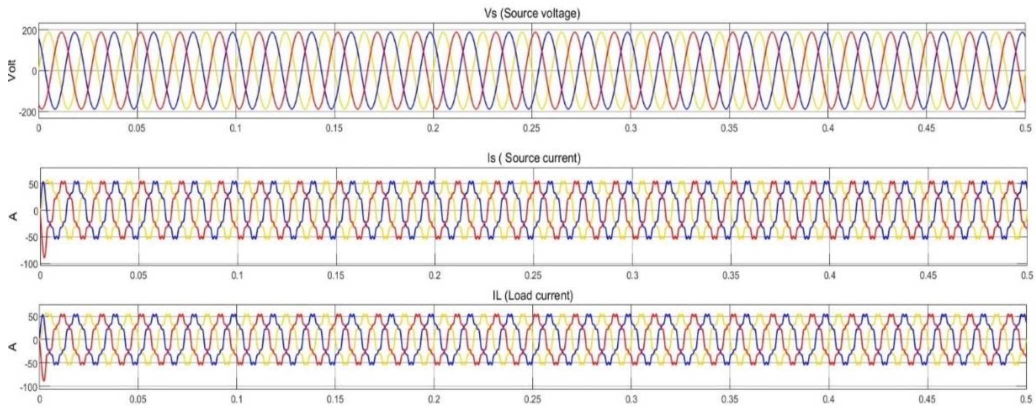

Figure 12 Response of the system without compensation

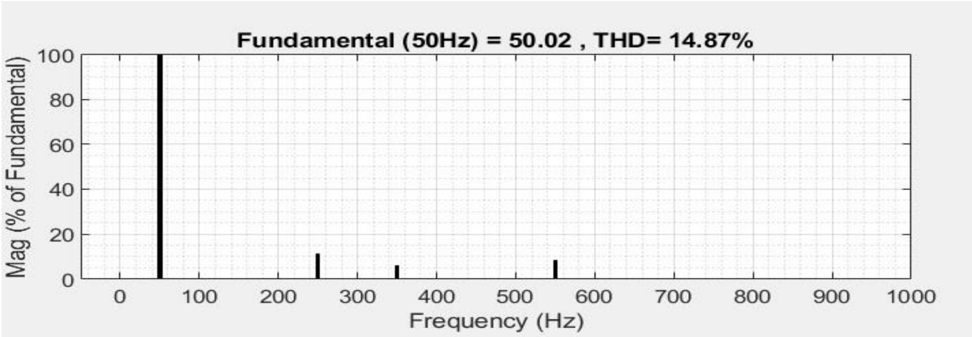

Figure.13 Source Current Distortion analysis using FFT

b) Simulation result with Passive filter

When the passive filter is utilised in alone, it is noted that the total harmonic distortion (THD) experiences a decrease from 14.87% to 10.05%. Furthermore, the inclusion of a double-tuned passive filter results in a reduction of both the 5th and 7th-order harmonics. Figure 14 demonstrates an enhancement in the source current distortion response of the system. Figure 15 illustrates the THD analysis.

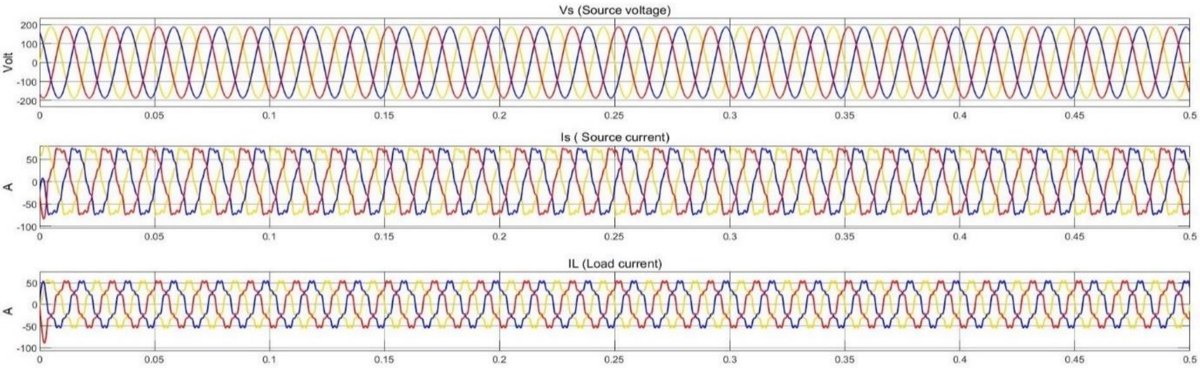

Figure 14. Response of the system with passive double tuned filter compensation

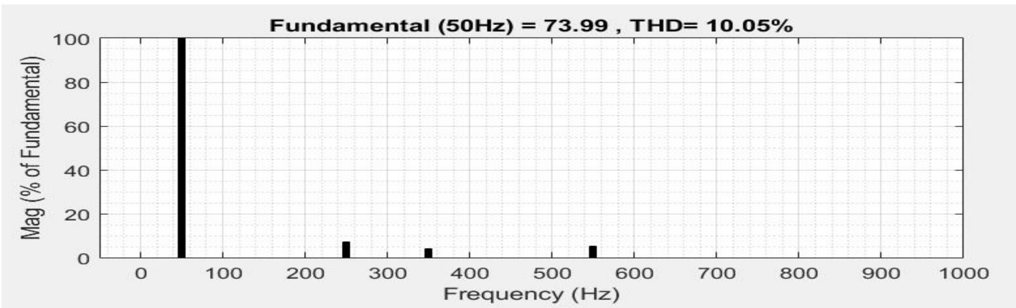

Figure 15 Source Current THD analysis with passive filter compensation

c) Simulation result with Hybrid Filter

Fig. 16 depicts the performance of the hybrid filter presented in this study, which integrates both passive and active filters for mitigation purposes. The total harmonic distortion (THD) of the source is decreased to 0.50%, falling within the IEEE-519 standard range. The compensation of the shunt active filter was successfully accomplished by the utilisation of instantaneous power theory for the generation of reference current. This was accomplished by employing a PI controller for the regulation of DC voltage and an HCC for the generation of switching pulses. **Fig .17** illustrates the waveform of the source current, with a total harmonic analysis conducted using the hybrid filter. According to the examination of waveforms and harmonic spectra the utilisation of a hybrid filter significantly decreases the overall harmonic distortion. The outcome is presented in **Table VI**.

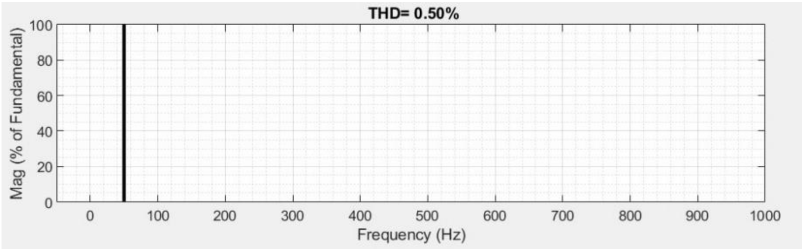

Figure.16 Source Current THD analysis with Hybrid Filter compensation

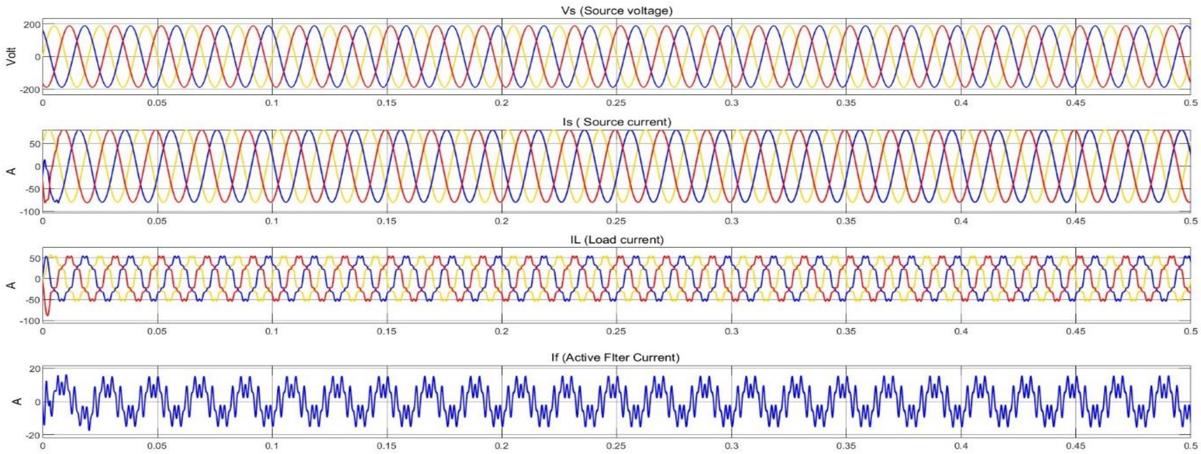

Figure 17 Response of the system with Hybrid filter compensation

Table IV Comparison of % THDi

Without Filter	With Passive Filter	With Hybrid filter
14.87%	10.05 %	0.50 %

V. CONCLUSION.

In this research, the case study of the Padamavati pulp and paper mill is thoroughly examined in order to conduct harmonic analysis and provide an appropriate mitigation strategy. The Simulink model of the system is developed in MATLAB Simulink to match data obtained in the harmonic analysis survey conducted by InstaSine Power Technologies Private Limited using the Fluke-434 power quality analyzer. This work uses MATLAB Simulink to construct a nonlinear model that can alter the THD value for various harmonics to match the case study data. A multilevel inverter-based hybrid filter with passive and active filters is simulated in MATLAB to decrease harmonics. System effectiveness is examined without and with different compensating methods. Using a passive filter reduces system current THD from 14.87% to 10.03%, with a decrease in dominating 5th and 7th order harmonics. Multilevel inverter-based hybrid active filters reduce THD to 0.50%, demonstrating their efficacy. A nonlinear load model that matches field-measured data and effective reduction approaches are the key contributions of this work. The hybrid active filter outperforms others in simulations.

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