Harmonic Measurement And Mitigation In Variable Frequency Drive: A Case Study

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Abstract— Utility of non-linear load leads to generation of harmonics in industry which is affecting the power quality. Variable frequency drive is the main source of harmonics in industry. Harmonic analysis to obtain the harmonic content of current and voltage have become vital tasks in context with increasing power quality. This paper discusses the various sources, measurement and mitigation techniques in context with harmonics generated in industrial load. Paper proposes second order active low pass filter and passive low pass power filter technique for harmonic measurement and its mitigation. Design of both filters is also presented. Paper also highlights the experimental analysis of the proposed technique to observe the reduction of current harmonics at VFD installed in one of the industry. The experimental result shows that the proposed system is compatible with the standard instrument and can reduce harmonics up to the desired limit.

Keywords- *Harmonics, non-linear loads, VFD, Design, Filters.*

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I. Introduction

In electrical power system harmonics have been shown to have deterious effects on power electronic devices including adjustable speed drives, controlled rectifier, and variable frequency drives (VFDs) etc. VFDs are widely used in energy cost savings (20-30% savings) aspect. Variable speed drives reduce energy and decrease pollutant emission levels to environment while increasing productivity, their proliferation is inevitable [9]. In spite of advanced technology and improved reliability of modern VFDs, they are considered not only as harmonic sources but also interharmonic sources.

In ideal situation, the electric power in a network is supplied at a constant frequency, and at specified voltage magnitudes known as the fundamental frequency, however, in practice under different circumstances the frequency and voltages are deviated from their designated values. The deviation of a wave form from its perfect sinusoidal is generally expressed in terms of harmonics. Harmonics in power systems is nothing but the existence of signals, superimposed on the fundamental signal, whose frequencies are integer numbers of the fundamental frequency. The presence of harmonics in the voltage or current waveform leads to a distorted signal for voltage or current, and the signal becomes non-sinusoidal signal which causes malfunctions or damage on load. Thus Harmonic measurement has become one of the well-known aspects of power quality monitoring and control [8]. To address the problem of harmonic measurement in non-stationary scenarios, a number of signal processing techniques have been proposed in recent years such as, Fast Fourier transform (FFT)[10][12] ,application of adaptive filters[13]. SVD [11] [14]. And wavelet based technique [20]. Also there are various techniques available for the mitigation of harmonics present in the system. Amongst all the techniques filters are majorly used for harmonic mitigation.[5] Filters are of two types active and passive. Active Power Filters (APF) are made up of power electronic devices and Passive filters are made up of Resistor, Inductor and Capacitor elements. Most of the filtering techniques have common drawback of higher cost compared to passive filtering techniques. In This paper for harmonic measurement a 2nd order active low pass filter bank has been designed up to 8th harmonic to differentiate the harmonic components. The identified harmonic contents has been mitigated using, a passive low pass power filter which has been designed to filter out the higher order frequency components. Passive filters offers both power-factor correction and high current-filtering capacity. Since, they are simpler and cheaper as compared to active filters, passive filtering approach is considered for harmonic mitigation in most of the applications.

The paper is organized as follows:
Section II, briefly describes the Impact of harmonics on Variable frequency Drives in industry. In Section III design of Active low pass filter is presented for harmonic measurement. Section IV presents the design of Passive Filter for Harmonic Mitigation. Experimental results of the designed system is presented in Section V. Section VI concludes the paper.

II. Variable Frequency Drive

Variable frequency drives (VFDs) are widely used in industry for important loads in their operations [4]. VFD has great advantages such as speed control, energy saving and motor's starting current limitation. VFD converts 60 Hz

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power, for example, to a new frequency in two stages: the rectifier stage and the inverter stage (fig.1). The conversion process incorporates three functions:

a) Rectifier stage: A full-wave, solid-state rectifier converts three-phase 60 Hz power from a standard or higher utility supply to either fixed or adjustable DC voltage. The system may include transformers if higher supply voltages are used.

b) Inverter stage: Electronic switches power transistors or thyristors - switch the rectified DC on and off, and produce a current or voltage waveform at the desired new frequency. The amount of distortion depends on the design of the inverter and filter.

c) Control system: An electronic circuit receives feedback information from the driven motor and adjusts the output voltage or frequency to the selected values. Usually the output voltage is regulated to produce a constant ratio of voltage to frequency (V/Hz). Controllers may incorporate many complex control functions

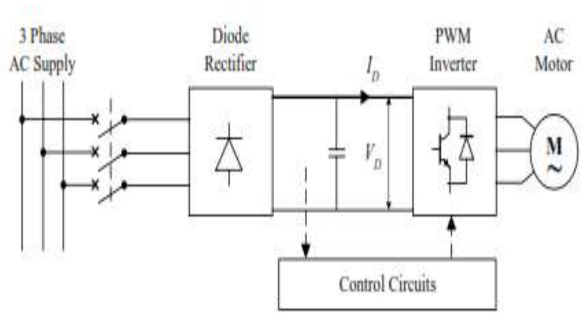

Figure.1 Variable Frequency Drive

A. *Input Current Harmonic Distortion of VFD Systems*

An ASD system with a basic 6-pulse diode bridge rectifier, shown in Fig.1.has typically an input line current waveform as shown in Fig.2 Harmonics generated have 2p±1 order, where p is the number of pulses in the rectifier output DC voltage The pulse number of the rectifier is the determining factor in what the characteristic power system harmonics will be on a particular drive. The harmonics produced by a six-pulse rectifier will be the 5th, 7th, 11th, 13th, etc. Their magnitudes are roughly the inverse of the harmonic order times the magnitude of the fundamental (e.g., the 5th harmonic is about one fifth of the fundamental current). A twelve-pulse drive will exhibit harmonics at the 11th, 13th, 23rd, 25th, etc. Twelve-pulse drives will produce small amounts of 5th, 7th, 17th, and 19th harmonics (typically on the order of 10% of the levels for a six-pulse drive).

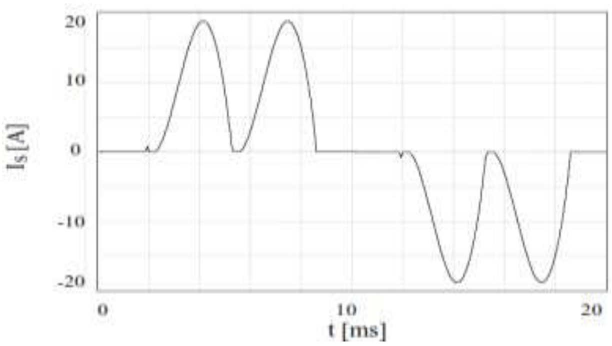

Figure.2 Diode bridge rectifier front-end ASD system (5.5kW) (a): Line current waveform

B. *Applications*

Variable speed drives are used for two main reasons:
(a) To improve the efficiency of motor-driven equipment by matching speed to changing load requirements.
(b) To allow accurate and continuous process control over a wide range of speeds.

III. HARMONIC MEASUREMENT IN VFD

Various signal processing techniques are available for harmonic measurement as previously discussed. Since, it is costly industry needs simple and economic technique to identify the present harmonic contents in the system in order to mitigate it. This section describes the Design of Active filter for harmonic measurement it consists of two parts:

A. Active Filter
B. Microcontroller Section

A. *Active Filter*

A second order active low pass filters has been designed up to 8^{th} harmonic to differentiate the harmonic components. Circuit have been designed in such a manner that there will not be additional data insertion and no disturbance to original signal. The circuit diagram of the filter is shown in fig.3

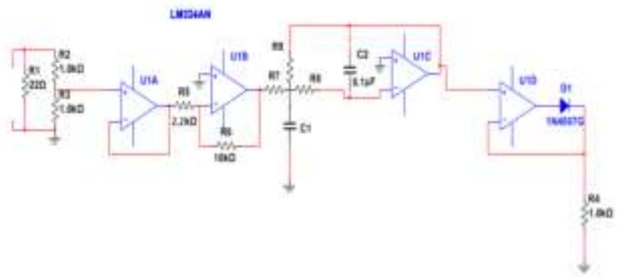

Figure.3 : Second Order Active Filter

In this circuit LM324 operational amplifier is used which has four opamp inside it. It works on +/- 12v or single supply also. It has very low offset. The first stage of the circuit is the buffer Amplifier (U1A) which avoids loading on current transformer to preserve nature of waveform and it also isolate the CT from other circuit. The output of buffer amplifier or unity gain amplifier is given to gain amplifier (U1B) so as to amplify the weak signal if required. It is inverting amplifier. The filter part is implemented using second order filter (U1C) with different harmonic components as tuning frequency F_0. The output of the filter contains selected ac components with both polarity and cannot be given to analog to digital converter. It has to be converted to dc. It is done using precision rectifier (U1D) using op-amp. Then the output of the precision rectifier is given to analog to digital converter which is below +5v dc.

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Designing equations for the calculation of components can be given as follows:

$$\text{Gain: } K = -\frac{R_6}{R_5} \qquad (1)$$

$$C_1 = 4Q^2(1 + |K|)C_2 \qquad (2)$$

$$\text{Where, } Q = \frac{1}{3 - |K|}$$

$$R_1 = \frac{1}{2|K|\,\omega_o QC_2} \qquad (3)$$

Where, $\omega_o = 2\pi f_o$

$$R_2 = \frac{1}{2\omega_o QC_2} \qquad (4)$$

$$R_3 = \frac{1}{2(1 + |K|)\omega_o QC_2} \qquad (5)$$

The signal will be taken from current transformer. The current transformer acts as line sensor which converts higher amplitude of current to lower amplitude The output of current transformer once converted to voltage it will be then processed further using designed op-amp circuit.

B. Microcontroller section

A microcontroller circuit has been designed to sense and display harmonic levels and to send the data to PC The main parts of this circuit are (i) Analog To Digital Converter (ADC), which has 8 channels to which signal up to 5v dc can be connected i.e. filter output (ii) Microcontroller (Intel 89c51), It is the main part of the circuit has advantage that is it's development system is easily available (iii)Local display: displays the data on LCD in proper form iv) PC interface which is done using IC MAX 232 it sends the data to PC for graphical display.

IV. HARMONIC MITIGATION USING PASSIVE FILTER

The different methods of eliminating harmonics K-factor transformers and drive isolation transformers, Multi pulse drive configurations (6 pulse, 12 pulse,18 pulse and 24 pulse) Active harmonic filters (AHF) Hybrid harmonic filters amongst all the methods available passive filters are favorably used because of their simple structure, filter components are passive and rugged, and the filter design and implementation procedure is relatively easy and most importantly the filter cost is low, Passive filters are of series and shunt passive filter. Series passive filters can be purely inductive type or LC tuned type. It blocks the harmonics by providing high impedance path at specific frequencies and shunt passive filter provides low impedance path to current at harmonic frequencies reducing the flow of harmonic current components to the source side. The basic principle of using passive filter is that on the tuned frequency filter will offer low impedance to current through which harmonic current will tends to divert in the system. One more advantage of employing passive filter is that it comes with the property of reactive power compensation [14] In this work, we have designed passive low pass power filter, an *LC* π filter which is a capacitor filter followed by an *LC* circuit. This components are designed for the high rating, as per the application. An *LC* π filter can be shown as in fig.4.

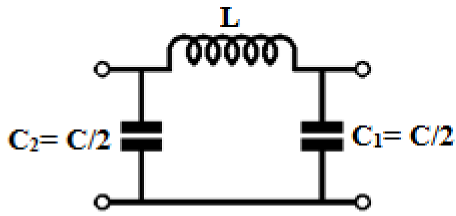

Figure. 4**:** LC pi Filter

The LC filter provides good filtering action over a wide range of currents. The capacitor filters best when the load is drawing little current. So, the capacitor discharges very slowly and the output voltage remains almost constant. However, the inductor filters best when the current is highest. The complementary nature of these two components ensures that good filtering will occur over a wide range of currents.
The values of the *L* and *C* are selected according to the cut-off frequency. The cut-off frequency can be taken between 60Hz to 100Hz.
The designing equations to find the values of inductor and capacitors are given as follows:

$$\omega_o = \frac{1}{2\pi\sqrt{LC}} \qquad (6)$$

V. EXPERIMENTS AND RESULTS

The system is designed for harmonic measurement & its mitigation. This system has the block diagram (fig.5)

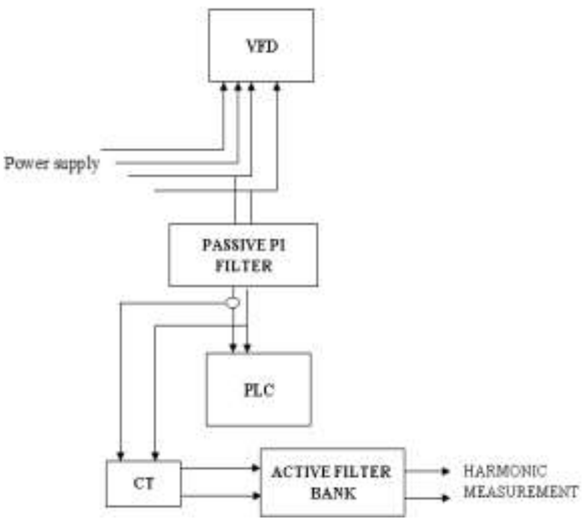

Figure.5: Block Diagram of the System

To evaluate the performance of the designed system, experiments have been carried out with non-linear load. These loads are: (i) VFD (installed at PLASTECH SOLUTION, EN ISO 9001:2008 Certified Company, Pune (MH))

The measurement of harmonics has been taken at two different stages. First stage of measurement has been taken without using passive filter and second stage of measurement has been taken after mitigation

A. VFD

VFD is a source of harmonic which is used in molding machine This VFD has 25 kW and 20 HP power ratings. The measurements have been taken at three stages:

1. Harmonic level measurement at the Source (VFD) (Table no. 1 and figure 6).
2. Harmonic level measurement without filter (at PLC)) (Table no. 1 and figure 7).
3. Harmonic level measurement with filter (at PLC) (Table no. 1 and figure 7)

TABLE I.

Frequency (Hz)	Cumulative Harmonics level		
	At Source (VFD)	At PLC	
		Without Filter	With Filter
50	14	4	4
100	15	5	4
150	26	6	5
200	29	7	6
250	31	7	6
300	34	8	6
350	41	9	7
400	42	10	7

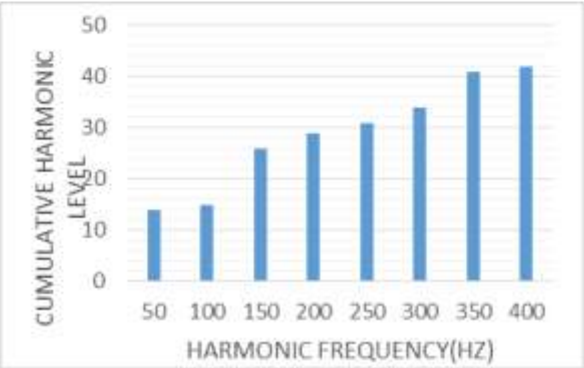

Figure.6: Harmonic levels at VFD

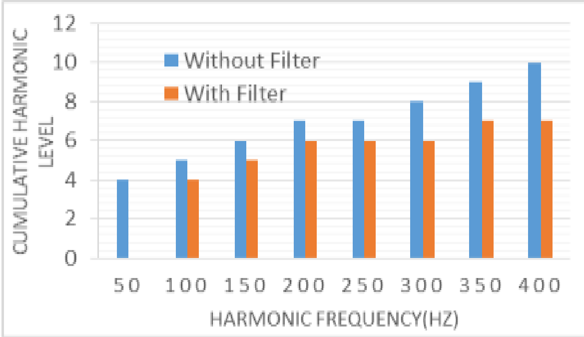

Figure.7: Harmonic levels at PLC without and with filter

From table no. 1 and figure 6, it is observed that for VFD the 3rd and 7th harmonics are severe. These harmonics causes effect on PLC to thus harmonics at PLC has been reduced effectively, with the use of passive filter (table 1 and figure 7).

VI. CONCLUSION

In industry large number of VFD's are installed for different operations, These Diode rectifier front-end based VFDs without appropriate filtering technique injects significant amount of current harmonics to the AC line and pollute the system resulting in power quality problems. Therefore it becomes important in industry to measure harmonic contents and mitigate it using proper technique. This paper presented design of second order low pass filter for harmonic measurement. Using active filter harmonics level have been measured and it is observed that 3rd and 7th harmonics were dominant at the source(VFD) to mitigate these harmonics passive low pass filter is designed. It is found that using passive filter dominant harmonics reduced to the significant level. This designed model is simple, accurate, and easy to modify. For the better harmonic reduction, hybrid filter by using passive and active filter combination can be developed.

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