Straight Talk about Harmonic Problems and Case Study for using AC Drives in Pulp and Paper Industries

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ABSTRACT

Though much has been written about harmonics and related issues with respect to AC drive, many drives users still seek clear answers to some basic questions. The purpose of this paper is to provide the interested reader with some basic information regarding AC drives and harmonics with a simplified explanation of harmonics, showing how can affect a distribution system and this paper describes the investigation of harmonics from 6-pulse and 12-pulse AC drives in pulp and paper industries. It is the intention of the author to dispel some of the myths as well as point out legitimate concerns, show some viable solutions and their pros and cons.

Drive basics:

Before we can have a meaningful discussion on harmonics with respect to AC drives, first it is necessary to have a good understanding of the basic workings of a modern PWM Six Pulse AC drive, specifically how it draws power from the utility line. Figure 1 below is a schematic diagram of a typical "voltage source" Six Pulse AC drive power structure.

A modern AC drive power structure consists of three basic stages. This is because the inverter section shown in figure 1 requires a stable DC source to operate. Therefore, the first stage of the drive must convert three-phase AC to DC.

The first stage is known as the converter section. In an AC drive, the converter stage consists of a three phase, full wave Diode Bridge, though SCRs (Silicon controlled rectifiers) are sometimes used in place of diodes. If this stage were isolated from the rest of the power structure, we would see a DC voltage with a 360 Hz ripple at the DC bus connection when 3 phase power is applied to the input (see figure 2).

A filter is required to smooth out the ripple on the DC bus in order to run the IGBT inverter. Therefore, a second or "filter" stage is required. Primarily, this consists of a large capacitor bank.

The third stage is the inverter section. This section uses high-speed Transistors/IGBTs as switches to apply a PWM (Pulse Width Modulated) waveform to the motor. Taking advantage of the fact that a motor is basically a large inductor, and that current does not change very fast in an inductor, the DC bus voltage can be applied in pulses of varying width in order to achieve current in the motor that approximates a sine wave.

Upon application of AC power the capacitor will charge up to the peak of the applied line voltage through the diode bridge. It allows current to flow in one direction. When a load is applied to the DC bus, the capacitor will begin to discharge. With the passing of the next input line cycle, the capacitor only draws current through the diodes and from the line when the line voltage is greater than the DC bus voltage. This is the only time a given diode is forward biased. This only occurs at or near the peak of the applied sine wave resulting in a pulse of current that occurs every input cycle around the +/-peak of the sine wave.

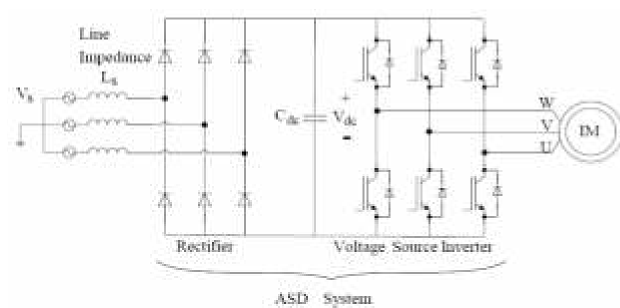

Figure 1. Six Pulse AC Drive Power Structure

As load is applied to the DC bus, the capacitor bank discharges and the DC voltage level drops. A lower DC voltage level means that the peak of the applied sine wave is higher than the capacitor voltage for a longer duration. Thus the width of the pulse of current is the peak of the applied sine wave is higher than the capacitor voltage for a longer duration. Thus the width of the pulse of current is determined in part by the load on the DC bus. Figure 2 shows input line voltage V_{ac}, Filtered DC bus voltage V_o and the pulsating Input Current I. Note that the V_o trace in black would be before the filter capacitor is added to the circuit.

The aforementioned characteristics hold true for the three phase model with the difference being 6 diodes and 6 pulses per cycle. For an AC drive, the load is the Inverter section. One can see by looking at figure 2 that if we have a three phase diode bridge converter we get 6 of these voltage pulses for one complete three phase line cycle. It is the pulsating input phase current shown in figure 2 that gives us the term "nonlinear

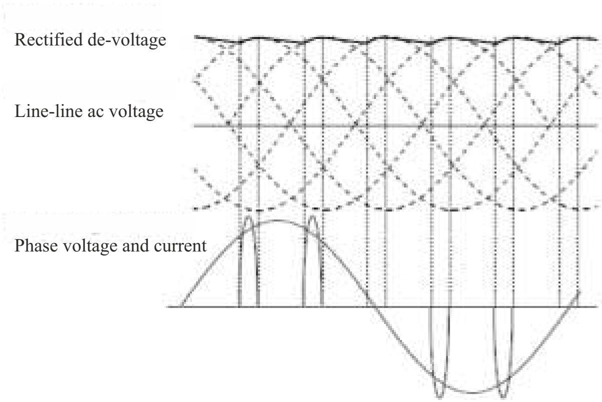

Figure 2 Three Phase Rectifier Voltage and Phase Voltage and Phase Current Waveform

load" since the current does not flow in proportion to the applied voltage.

In fact, with a nonlinear load, current may not flow at all for a major part of the applied voltage cycle. In a three-phase system, the widest conduction time possible would be 120 degrees (roughly +/-60 degrees from the peak). Once we go outside this 120 degree conduction window, one of the other two phases will have a higher peak voltage and current will flow from that phase.

Harmonics Explained

Now that we understand how current is drawn from the AC line by a drive, let's try to define the term "harmonics". Looking at the waveforms in figure 3 we can see that each waveform is close to a perfect sine wave. This is a linear load and contains no harmonics. A perfect sine wave by definition has no harmonics but rather one fundamental component at one frequency. The fundamental waveforms in figure 3 are sine waves at one frequency. We saw that nonlinear loads such

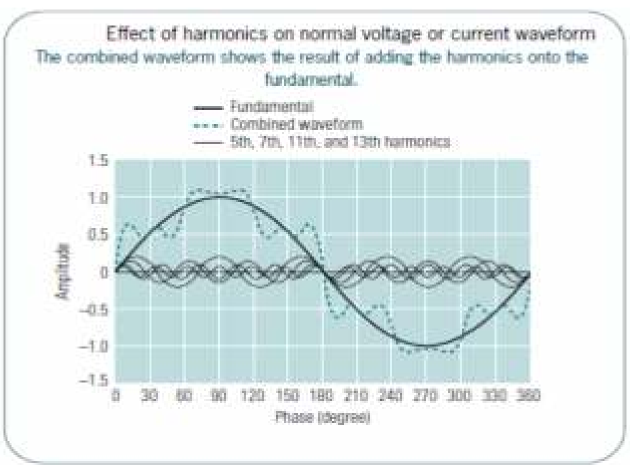

Figure 3 Fundamental Phase Current Waveform and Harmonic currents

as AC to DC rectifiers produce distorted waveforms. Harmonics are present in combined waveforms in figure 3 that are not perfect sine waves due to distortion from nonlinear loads.

A French mathematician named Fourier discovered that a distorted waveform can be represented as a series of sine waves each an integer numbers multiple of the fundamental frequency and each with a specific magnitude. For example, the 5^{th} harmonic on a system with a 50 Hz fundamental waveform would have a frequency of 5 times 50 Hz, or 250 Hz. These higher order waveforms are called "harmonics".

Effects of Harmonic Distortion

The effect of current distortion on power distribution systems can be serious, primarily because of the increased current flowing in the system. In other words, because the harmonic current doesn't deliver any power, its presence simply uses up system capacity and reduces the number of loads that can be powered. Harmonic current occur in a facility's electrical system can cause equipment malfunction, data distortion, transformer and motor insulation failure, overheating of neutral buses, tripping of circuit breakers, and solid-state component breakdown. The cost of these problems can be enormous. Harmonic currents also increase heat losses in transformers and wiring. Since transformer impedance is frequency dependent, increasing with harmonic number, the impedance at the 5^{th} harmonic is five times that of the fundamental frequency. So each ampere of 5^{th} harmonic current causes five times as much heating as an ampere of fundamental current. More specifically, the effects of the harmonics can be observed in many sections of electrical equipment and a lot machines and motors. These effects can be described in more details as follows:

Effects of Harmonics on Rotating Machines

For both the synchronous and the induction machines, the main problems of the harmonics are increasing on the iron and copper losses, and heating by result of the high current caused by harmonics as a result reducing the efficiency. The harmonics can be a one reason as an introduction of oscillating motor torque. Also, the high current can cause high noise level in these machines.

Effects of Harmonics on Transformers

Transformers are designed to deliver the required power to the connected loads with minimum losses at fundamental frequency. Harmonic distortion of the current, in particular, as well as the voltage will contribute significantly to additional heating. There are three effects that result in increased transformer heating when the load current includes harmonic components:

a. RMS current.

If the transformer is sized only for the KVA requirements of the load, harmonic currents may result in the transformer rms current being higher than its capacity. The increased total rms current results increase conductor losses.

b. Eddy-current losses.

These are induced currents in the transformer caused by the magnetic fluxes. These induced currents flow in the windings, in the core, and in the other connecting bodies subjected to the magnetic field of the transformer and cause additional heating. This component of the transformer losses increases with the square of the frequency of the current causing the eddy current. Therefore, this becomes a very important component of transformer losses for harmonic heating.

c. Core losses.

The increase in core losses in the presence of the harmonics will be dependent on the effect of the harmonics on the applied voltage and the design of the transformer core. Increasing the voltage distortion may increase the eddy currents in the core laminations. The net impact that this will have depends on the thickness of the core laminations and the quality of the core steel. The increase in these losses due to harmonics is generally not as critical as the previous two.

Effects of Harmonics on Lines and Cables

The main problems associated with harmonics are: increased losses and heating, serious damages in the dielectric for capacitor banks and cables, appearance of the corona (the amount of the ionization of the air around the conductor or the transmission line) due to higher peak voltages and corrosion in aluminum cables due to DC current.

Effects of Harmonics on Converter Equipments

These equipments can be expressed as switches or On-Off equipment because of the switching the current and voltage by some devices such as diodes and thyristors. These converters can switch the current so, creating notches in voltage waveforms, which may effect the synchronizing of the other converter equipment. These voltage notches cause misfiring of the thyristors and creating unarranged other firing instances of the other thyristors in the equipment.

Effects of Harmonics on Protective Relays

The protective devices such as circuit breakers and fuses are designed to trip out in specific current and voltage and through very specific short time. The presence of the harmonics causes the difference on the voltage and current. So, this can cause failing tripping of these protective equipment. Also, the harmonics can let the relays to operate slower and/or at higher pickup values. Over current and over voltage can cause improper operation for relays. However, this cause the unsuitable tripping time so, causing some serious damages as far as fire occurs.

Case study

Consider the Industrial plant under study shown in Fig-4. The industrial plant is supplied from 24.5 MW T.G through Distribution transformers 1 and 2 of 2 MVA, Dyn11, and 11 KV/415V. The loads consist of 12-pulse and 6-pulse converters. By studying the equivalent impedance of the system at Distribution panel (PCC) 1 and 2, the table's I-II presents the line voltage at bus and its harmonics %thd U and the line current through main transformer and its harmonics %thd I. From the results we can see Distribution panel-2 harmonic currents exceed the standard limits of the IEEE Std. 519.

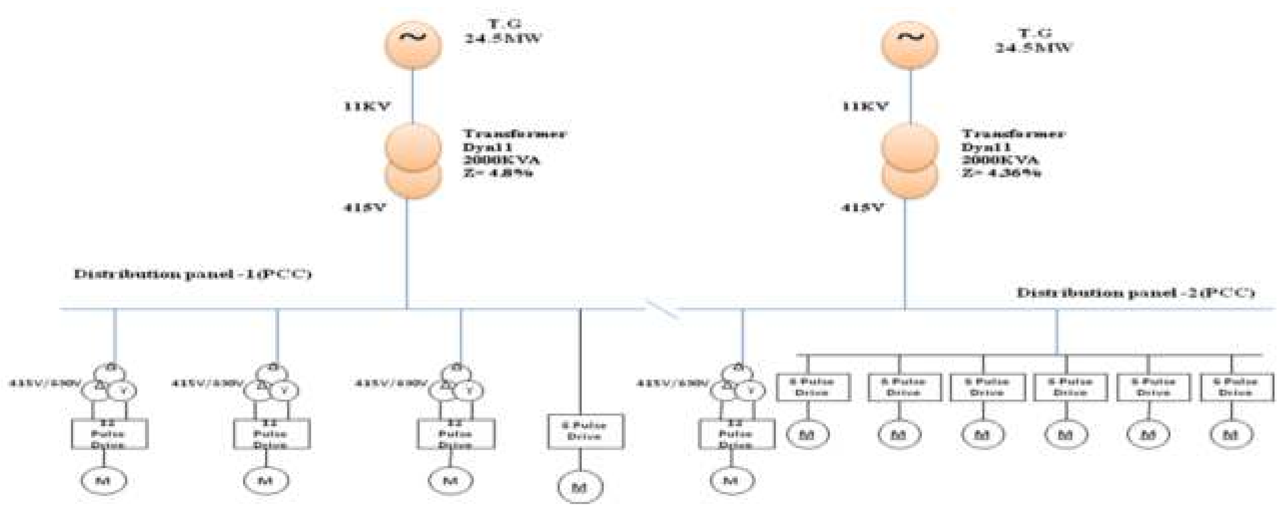

Figure 4 Recovery Boiler power Distribution and showing the Drives Installation.

Table- I. Measured values in Distribution panel (PCC-1)

	Urms (V)	Irms (A)	thdU (%)	thdI (%)	Uxx	S (kVA)	P (kW)	Q (kVAR)	Pf	Freq
Ph1	234.95	1043.022	1.66	4.52	404.72	245.054	219.307	109.343	0.895 i	
Ph2	232.95	992.325	1.37	5.05	406.19	231.162	197.544	120.050	0.855 i	
Ph3	235.17	934.592	1.53	6.85	406.82	219.788	197.933	95.546	0.901 i	
Tot	I null:	0.000				695.374	614.784	324.939	0.88 i	49.45

Table- II. Measured values in Distribution panel (PCC-2)

	Urms (V)	Irms (A)	thdU (%)	thdI (%)	Uxx	S (kVA)	P (kW)	Q (kVAR)	Pf	Freq
Ph1	236.26	524.475	1.98	6.32	407.69	123.915	111.072	54.935	0.896 i	
Ph2	234.38	553.069	1.91	6.28	411.71	129.628	117.422	54.913	0.906 i	
Ph3	237.64	556.191	1.63	6.69	407.31	132.175	121.277	52.556	0.918 i	
Tot	I null:	31.777				385.636	349.772	162.404	0.91 i	49.33

Six pulse Drive

The 132 KW PA fan six pulse drive were investigated in Recovery Boiler. The three phase line voltage and current wave form and its Harmonic spectrum are shown in figure-5.A six pulse converter would generate harmonic current of the order 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th} 23^{rd}, 25^{th}, etc.

The Fig-6 shown phase current wave form using 3% line inductor at Total harmonic distortion of 33.87%.

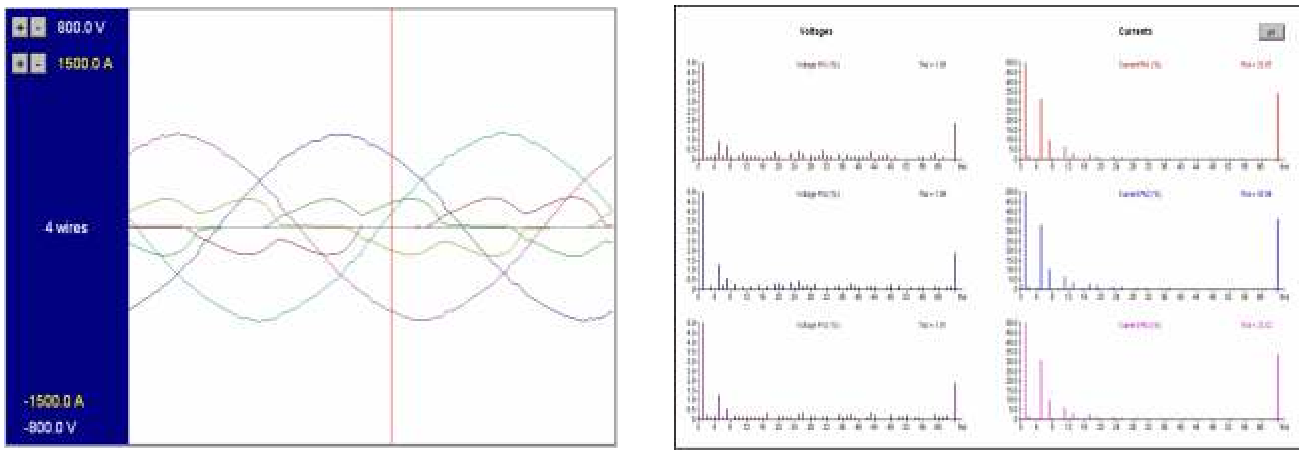

Figure 5 Line Voltage and Current Waveform and Harmonic spectrum

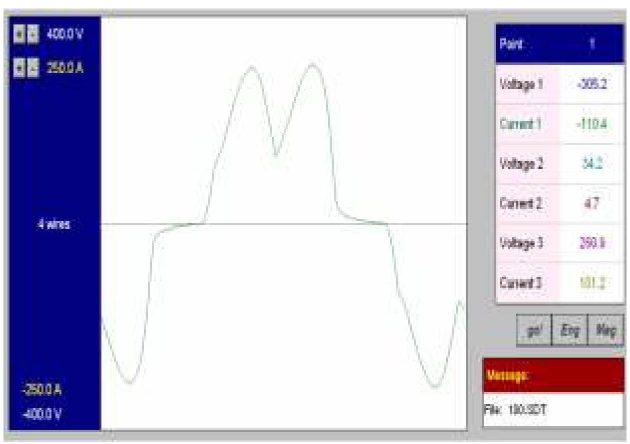

Figure 6 Phase Current Waveform

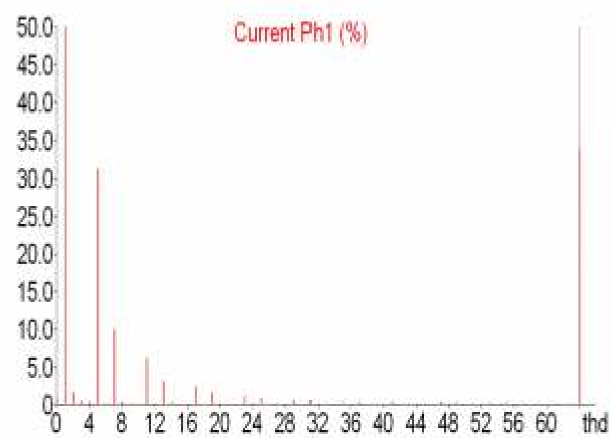

Figure 7 Phase Current Harmonic spectrum

Table-III Voltage distortion

Harmonic order	Phase voltage	% distortion	% standard limit
1	237.31	-	-
5	2.28	0.96	3.0
7	1.63	0.69	3.0
11	0.70	0.30	3.0
13	0.35	0.15	3.0
17	0.28	0.12	3.0
19	0.94	0.40	3.0

Table-IV Current distortion

Harmonic order	Phase Current	% distortion	% standard limit
1	116.41	-	-
5	36.45	31.31	7.0
7	11.62	9.98	7.0
11	7.33	6.30	3.0
13	3.72	3.19	3.0
17	2.88	2.48	2.0
19	2.01	1.72	2.0

12 Pulse Drive

Phase shifting involves separating the electrical supply into two or more outputs, each output being phase shifted with respect to each other with an appropriate angle for the harmonic pairs to be eliminated. The concept is to displace the harmonic current pairs in order to bring each to a 180^0 phase shift so that they cancel each other out. Positive sequence currents will act against negative sequence currents, where as zero sequence current act against each other in a three phase system. Recall that triplen harmonics are zero sequence vectors; 5^{th}, 11^{th}, 17^{th} harmonics are negative sequence vectors, and 7^{th}, 13^{th}, 19^{th} harmonics are positive sequence vectors.

Hence, an angular displacement of:
60^0 is required between two three-phase outputs to cancel the 3^{rd} harmonic currents.
30^0 is required between two three-phase outputs to cancel the 5^{th} and 7^{th} harmonic currents.
15^0 is required between two three-phase outputs to Cancel the $11^{th}$and 13^{th} harmonic currents.

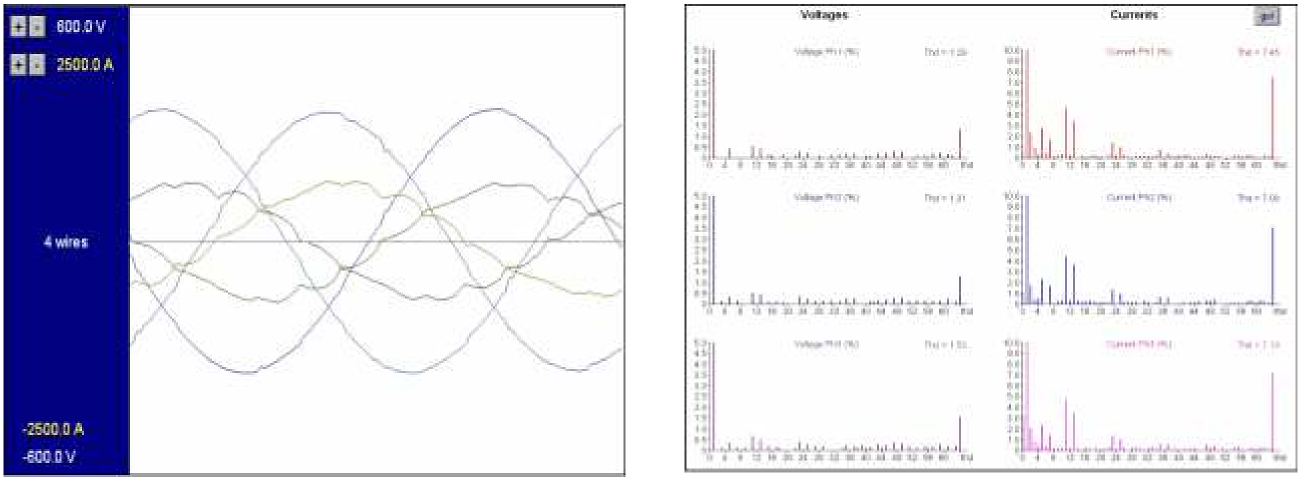

Figure 8 Line Voltage and Current Waveform and Harmonic spectrum

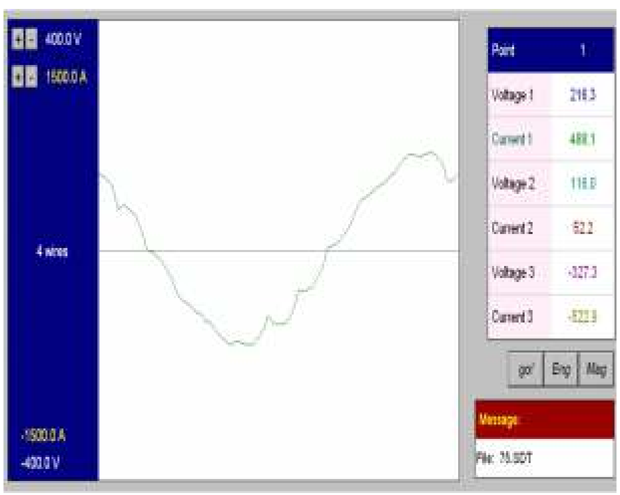

Figure 9 Phase current wave form

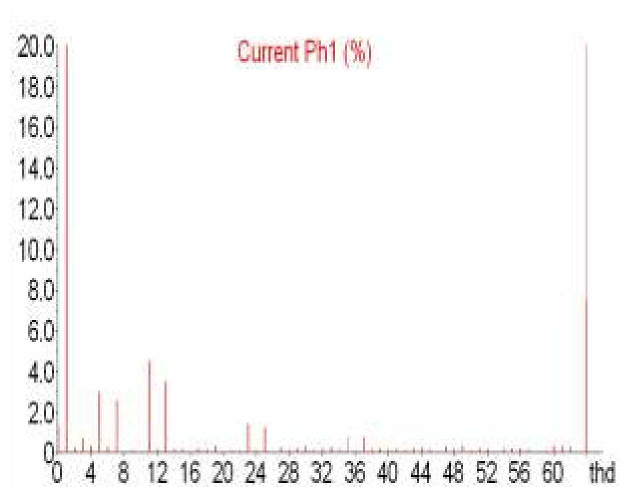

Figure 10 Phase Current Harmonic spectrum

Table-V Voltage distortion

Harmonic order	Phase Voltage	% distortion	% standard limit
1	236.86	-	-
5	0.98	0.41	3.0
7	0.11	0.05	3.0
11	1.33	0.56	3.0
13	1.03	0.44	3.0
17	0.19	0.08	3.0
19	0.35	0.15	3.0

Table-VI Current distortion

Harmonic order	Phase Voltage	% distortion	% standard limit
1	236.86	-	-
5	0.98	0.41	3.0
7	0.11	0.05	3.0
11	1.33	0.56	3.0
13	1.03	0.44	3.0
17	0.19	0.08	3.0
19	0.35	0.15	3.0

The 315 KW SA fan 12- pulse drive were investigated in Recovery Boiler. The three phase line voltage and current wave form and its Harmonic spectrum are shown in figure-8. SA fan

connected to 12-pulse converter using 400KVA phase shifting Transformer.

The Fig-9 shown phase current wave in Total harmonic distortion of 7.47%.

Conclusions

It is inevitable that harmonics will be generated whenever an adjustable speed drive is used. The order and magnitude of these harmonics greatly depend on the drive configuration and system impedance. A three-phase machine connected to six pulse system will generate more harmonics when compared to a six-phase machine connected to twelve-pulse system. Harmonic losses in the stator and rotor must carefully be taken into account during design stages to keep motor temperature rise to acceptable limits. Harmonics fed back to the power system are reduced by the use of filters that are connected to the incoming power supply. These filters are relatively large and occupy substantial space in the substation yard. There is a great need for a coordination of decisions regarding acceptable harmonic levels between users, drive manufacturers, electric utilities and standards groups. This would certainly simplify the requirements for harmonic filters from the user's and manufacturer's point of view.

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